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PROJECT SQUID

SEMI-ANNUAL PROGRESS REPORT

1 JANUARY 1947

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NEW YORK UNIVERSITY

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SEMI-ANNUAL PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ORI-11, TASK ORDER II

NEW YORK UNIVERSITY
NEW YORK, NEW YORK
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FIGURES

I. THE GROWTH AND PRESENT STATUS OF PROJECT SQUID AT N. Y. U.

General Background. Work done by members of the Applied Mathematics Group, New York University, prior to July 1946, led to the publication in particular of a theoretical report on combustion and flow processes inside a pulse jet motor. This report is entitled *A Gas Dynamical Formulation for Waves and Combustion in Pulse Jets.*[1] It is evident from this and other reports that many of the fundamental physical phenomena associated with the operation of liquid fuel rockets and pulse jet motors are either unknown or incompletely understood. The problems thus uncovered by this basic research form the substance of most of the proposals submitted by NYU in connection with Project SQUID. The history and purposes of the approved phases of research as well as other proposals for future work are discussed in Section II of this report. The remainder of the report handles in more detail the progress made in the six month period from July to the present time in attacking technical problems and presents a few suggestions for extending this research.

Facilities. At University Heights, Bronx, there are in West Hall of NYU, offices, an electronics laboratory, a machine and welding shop and a photographic laboratory, and, in its own building, a thermo-mechanics and jet-testing laboratory. One of the rooms in West Hall previously used for office space is being converted into a small machine-shop and general work space. At Washington Square, Manhattan, there are offices at 53 Washington Square South[2] for theoretical research, and a general laboratory in the Main Building of NYU.

The physical equipment at both the Square and the Heights is generally available to all Project SQUID members at NYU. This equipment consists briefly of the following: In the shops there are a 16″ metal lathe and a 9″ metal lathe, a milling machine, a drill press, a shaper, arc and acetylene welding equipment, and general shop tools. In the laboratories, besides standard laboratory tools and equipment, there are oscillographs, amplifiers, and generators of various types, a centrifugal blower, a small spectrograph, spark induction coils, nitrogen tank, gas supply, shock and flame tubes, an electronic photometer, an Eastman III Hi-Speed Camera, and a General Radio 35 mm. continuous film camera.

Procurement. Because of the slow settlement of trucking and other strikes, and because of the lack of availability of certain types of equipment, even from War Surplus agencies, much needed material and equipment is slow in acquisition.

As a result of loss of time spent in procuring equipment, and in necessary construction of apparatus, as well as the short time that work has been going on in this long-time basic study, many of the results presented in this report are preliminary in nature, and indeed much of the discussion is restricted to descriptions of construction of apparatus or test procedures.

[1] AMG NYU #151, June 1946, prepared under Navy Contract NOa(s)-7370.

[2] Recently moved to 45 Fourth Avenue, New York 3, N. Y.

II. GENERAL REMARKS ON THE PHASES OF RESEARCH

On July 26, 1946, approval was granted by the Bureau of Aeronautics of the U. S. Navy for New York University to undertake the following phases of research under SQUID contract N6ori-11, Task Order II.

Phase 1. In connection with pulsating jet engines: to undertake theoretical and experimental investigations of (1) flame motions with controlled initial turbulence, (2) stationary flames with controlled turbulence, (3) suitable theoretical models based on the above observations, and (4) statistical mechanics of non-uniform gases.

Phase 2. In connection with liquid rockets and pulsating jet engines: (1) to measure the thermal conductivity and heat capacities of various steels and other materials used in jet engines, and to determine by use of adiabatic calorimetry and metallography how these parameters depend on the temperature and on the rate of heating; (2) to determine characteristic parameters for heat transfer between hot turbulently flowing gases and walls, by use of measurements of gas velocities, radiation intensities and wall temperatures; (3) to use the above in refined calculations of temperature changes in jet tubes.

Phase 3. In connection with liquid rockets and pulsating jet engines: (1) to observe flame and particle motion, pressures, temperatures, densities, and effects of turbulence in pulsating and rocket jet devices; (2) to study water stream analogs for gas motions in pulsating jets and rockets in order to determine characteristics of simple theoretical models; and (3) to use the above for theoretical treatments of the internal ballistics of jet devices on the basis of justified simple models.

Phase 4. In connection with liquid rockets and pulsating jet engines: to develop instruments for recording transient thrust and pressures, temperatures, and densities of hot oscillating gases, and gas velocities.

Phase 5. In connection with liquid rockets and pulsating jet engines: to study drag characteristics of pulsating jet and other devices under conditions of non-steady or of supersonic flow, using firing range photography, wind tunnel measurements, and theoretical investigations.

Originally, NYU made the following additional proposal which the Policy Committee gave a lower priority rating, but which NYU intends to submit for approval at a later date when other research is less pressing:

> "Systematic analysis of various methods for achieving augmentation in jet devices, with possible development of new propulsive devices of an intermittent jet type: (1) Theory (2) Experiment."

The above proposals for phases of research under Project SQUID at NYU were suggested by preliminary theoretical and experimental investigations with which several members of the Applied Mathematics Group under the N.D.R.C. were concerned during the last two years of World War II.

Phase 2 was based on the observation that steel alloys used in rocket chambers exhibited marked temperature dependence in their thermal conductivities and heat capacities, and furthermore exhibited large heat absorptions in several narrow bands of temperature above 600° C. (heats of crystalline change). Except for some data on a few British steels, practically no measurements of these thermal parameters were found to be available. Furthermore, under the high rates of heating involved in rocket walls it might be expected that there would be marked lags in the absorption of heat of crystalline change, and therefore that there would be an abnormal rise in temperature. Such factors could greatly affect the temperature and stress distributions in rocket walls during the firing periods. Phase 2 was therefore initiated to study these matters, and specific investigations in this field are described in Sections VIII and IX of this report.

Phase 4 was based on the observation that only rather crude instrumentation had been used during the war to study pulsating jet motors, and to a certain extent, rocket motors. Practically no accurate data are available on the time variation of pressures, temperatures, velocities, and thrusts (not to mention densities and gas composition) in non-steady jet devices, a lack of information which is mainly due to the undeveloped state of suitable instrumentation. To be useful the instruments' pick ups must not sensibly disturb the jet and must not be perturbed greatly by corrosion or by the mechanical or thermal oscillations associated with the jet.

In a standard pulse jet the pressure oscillates between about 5 psi and 40 psi (absolute) at a frequency of more than 40 cycles per second; the gas temperature oscillates from about 300° to 2,000° absolute; large mechanical oscillations of the jet walls also occur. During the war most attention was paid to rough average values for thrust, fuel rate, drag, and wall temperatures; but considerably more refined measurements are apparently essential in order to understand and to treat the internal ballistics of pulsating jet and rocket motors in a reasonably scientific way. Such a study may very well lead to major improvements in such devices. After a fairly exhaustive study of the literature and of specific instruments, the SQUID group at NYU has tentatively decided to concentrate on the following methods:

1. *To obtain oscillograms of oscillating temperatures in jets,* use photo-electric multiplier tubes to pick up radiation from sufficiently concentrated sodium and potassium additives. Experiments with the spectrum line reversal method appear to justify the use of Planck's law over the sodium and potassium line breadths, provided that the concentration of the element is above a value depending on the thickness of the layer of gas whose temperature is required.

2. *To obtain oscillograms of oscillating pressures and thrusts,* use magnetostriction, crystal, or condenser type pickups protected from the jet gases

by a water-cooled shield with small perforations for the communication of pressures. Careful calibration is important, and inertia effects due to mechanical vibration must be distinguished from pressure response.

3. *To determine flame and particle speeds*, use either high speed intermittent or streak photography with either direct, shadow, or schlieren optical systems.

4. *To obtain oscillograms of gas densities*, various methods based on scattering of particles and waves may conceivably be used and are being investigated in a preliminary way. It is of interest to record pressures, temperatures, and densities to see if the usual equation of state applies to the gas in a one-dimensionalized theory of turbulent jets.

Specific instrumentation is discussed in Sections XII and XIII below.

Phase 5 was suggested by Professor Courant at a time when it appeared that a full time theoretical aerodynamicist was about to join the SQUID Project at NYU. Several young aerodynamicists who were interviewed later were surprisingly cool towards the new field of non-steady flow but were interested in the currently popular field of shock waves around aerofoils. Since other projects are handling the aerofoil features of guided missiles such aspects are not regarded as appropriate for research under the SQUID Project. However, using the available staff, a start has been made at NYU in the theoretical treatment of non-steady drag on bodies of revolution which simulate pulse jet motors (see Section XIV). At a later time it is intended that related experimental investigations shall be made under conditions of pulsed flow, both subsonic and supersonic. At present it is not known whether or not a supersonic pulse jet is feasible, but the question will be investigated.

Phases 1, 3 and 4 were suggested by investigations which were outlined in a report, mentioned in Section I, and entitled *A Gas Dynamical Formulation for Waves and Combustion in Pulse Jets.* In this report it was pointed out that flame and wave propagation in pulse jets involve durations which are not negligible in comparison with the period of the cycle. It was also pointed out that unlike combustion in Bunsen burners and in non-turbulent combustible gases, a field which is relatively well-explored, the flames in pulse jets spread in the form of turbulently (or swirlingly) distorted clouds which continue to glow for several milliseconds. The swirling motion is probably produced by the sharp-edged air intake valve bank, and by inhomogeneous mixing of the fuel and the air. Presumably the swirling greatly increases the effective rate of diffusion of heat and of chain carriers and thereby produces the observed high rates of spread of the flames. When interpreted one dimensionally, these rates correspond to effective flame speeds of more than 200 feet per second relative to the gas (in contrast with flame speeds of several yards per second in non-turbulent mixtures). In order to make fairly accurate theoretical predictions of the performance and potentialities of pulse jet motors it is necessary to know how effective flame speeds and rates of combustion depend on the pressures, temperatures, and structure of the flow (or on the shape and dynamics of the swirl-making structures). To treat this problem fundamentally in terms of detailed reaction kinetics and eddy dynamics, appears to be out of the question at least in the immediate future. However, some relevant idealized investigations are being undertaken at NYU (see Sections IV, V, and VI).

A more immediately useful approach to a theoretical treatment of pulse jets with swirling combustion is believed to be provided in the above-mentioned AMG-NYU report, which presents a rather comprehensive one-dimensional gas dynamical-thermodynamical formulation for pulse jets of non-uniform cross section. This formulation provides a framework into which may be fitted empirical parameters in terms of which effective one-dimensionalized inlet and exhaust boundary conditions, flame speeds, and rates of release of chemical energy may be expressed. The determination of how these parameters depend on the external flow, the internal geometry, and the pressure, temperature, and composition of the fuel-air mixture is regarded as a matter for controlled experiment, by use of (i) stationary flames in ducts containing grids which simulate intake valve banks, (ii) moving flames in flame tubes containing suitable grids, and (iii) general observations on characteristics of actual pulse jets and their components. In (i) relatively simple instrumentation (e.g., involving pitot tubes for pressures and velocities and sodium line reversal for temperatures) could be employed to investigate the desired parameters under steady state conditions. These steady state parameters could then be tried in a theoretical treatment of dynamical cases, which could be checked experimentally in (ii) and (iii). If the steady state parameters were found to be inadequate for these dynamical cases, a more elaborate oscillographic instrumentation would be required to study dynamical factors involved in the parameters. In any event the parameters would be employed in theoretical calculations on pulse jets. If effective flame speeds of the order of a few hundred feet per second relative to the gas are developed in the stationary flame ducts (as they *are* developed in pulse jets), then, as is indicated in Section IV, very large blower equipment would be required to hold the flame stationary in a reasonably large duct without flame holders. (Flame holders are not ordinarily employed in pulse jets, which therefore differ considerably from ram jets in flame characteristics). Since such blower equipment is not available at NYU, negotiations were initiated in October 1946 for the use of blowers at the SQUID Project at Purdue University and at several other localities. These facilities or others may be available early in 1947 for flame tests and for the very noisy pulse jet and rocket tests which form an essential part of the research program as planned by NYU. Moving flames and small pulse jets can be and are being investigated in the NYU laboratories, and relevant descriptions are given in Sections III, VII, X, XI, and XII below.

A JB 2 pulse jet motor has been obtained from the A.A.F. at Wright Field, after a long delay due to the truck strike. The intake valve bank of the motor is to be studied under steady as well as artificially pulsed flow in a wind tunnel in order to obtain some values for the empirical parameters which are to be used in the boundary conditions in the one-dimensionalized theory referred to above. In this study, smoke tracer photography, pitot tubes, shadowgram movies, and pressure oscillograms will be employed.

III. FLAME TUBE EXPERIMENTS

Introduction. These experiments were initiated for the general purpose of determining the effect of turbulence (defined here to include swirling motions) on the speed of a flame moving down a tube. It is hoped that the data thus obtained will be of use in the development of a theory of combustion and flame propagation in turbulent mediums. Such a theory would have scientific interest in the fields of fluid dynamics and combustion theory. It would also be important in connection with the work in progress under Project SQUID because of the turbulent conditions which appear to exist in the combustion chamber of the pulse jet, and which appear to have a marked effect on the flame speed and the degree of combustion in the gases.

The speed of a flame (at low rates) relative to an observer is probably a function of three factors: (a) the movement of the medium in which the flame is traveling, (b) the shape and the area of the flame "front" as compared to the area of its cross section perpendicular to its general direction of propagation and (c) the speed of the flame relative to the gas mixture.[3] This fundamental speed (c) has been measured in three ways: (1) the Bunsen cone method in which measurements are made on the size of the inner cone of the flame and on the rate of flow of the mixture in order to determine the flame speed in a Bunsen burner, (2) the soap-bubble method in which simultaneous measurements are made of the radial speed of the flame and of the expansion of the gases enclosed in a soap bubble, thus allowing calculation of the fundamental speed, and (3) the method based on measurements of the shape of a flame front and its speed of translation during its motion down a tube.

These three methods have been used under conditions of non-turbulent flow, and all three have given fundamental flame velocities in the range from 1 to 30 ft./sec. When turbulence is created in the fuel mixture, flame velocities of a higher order result. The opinion of workers in the field has been that turbulence produces a local mixing of the burning and unburned gases, thus assisting in the diffusion of heat and of chain carriers and thereby increasing the speed of propagation of the flame. It is the magnitude of this effect of turbulence which we have set out to determine, under conditions which approximate as closely as is practicable the conditions in jet propulsive devices. We hope in addition to gain a better insight into the physical mechanism which produces the effect.

Apparatus. Motion pictures are taken of the motions of flames in a flame tube. The tube is a pyrex cylinder four feet long and four inches in diameter (Fig. 1). It is mounted vertically, and except when the tube is being filled with a combustible mixture, its bottom end is left open. At the top is an igniter, of which various types have been used. The types favored in the first experi-

[3] Coward and Payman, *Chemical Reviews, 21,* 359 (1937).

ments were (1) a flat spiral of coiled heater wire and (2) a sheet of iconel metal, both heated electrically to red heat to cause ignition. These planar igniters were chosen to allow ignition over the whole cross section of the tube, thus making the initial motion of the flame as nearly one-dimensional as possible. In recent experiments ignition was produced by means of a spark which facilitated the timing of the firing with the opening of a shutter in front of the movie camera.

Turbulence-making grids were mounted in a cylindrical holder which itself was held in place in the tube magnetically. Three grids have been used: No. 1 has a disc of copper fly screen; No. 2 is a waffle-like grid with twenty-one openings approximately three-eighths inch square; No. 3 is a waffle-like grid with three in-line openings each approximately one-half inch square. Grids Nos. 2 and 3 are shown in Figure 1.

Several flame experiments were performed to determine the effects produced by the presence of a wire helix hanging down inside the pyrex tube. Two sizes of helix were tried, one which fitted snugly into the tube and the other which had a diameter only about one half that of the tube.

In some recent experiments part of the pyrex

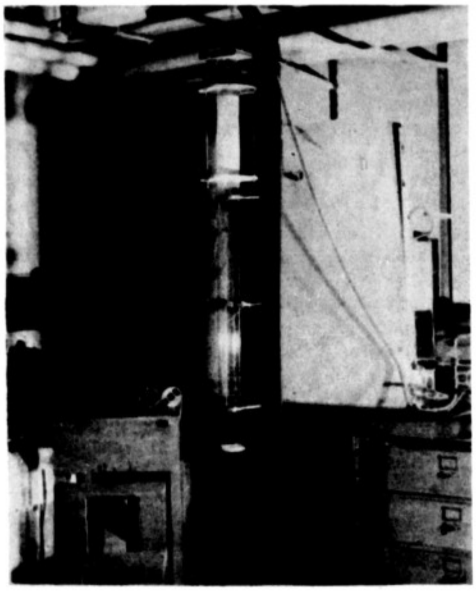

Figure 1. The flame tube with a latex section near the top.

tube was replaced by a flexible or by an easily ruptured sleeve (made of pleated thin latex or of wet tissue paper wrapped around a wire mesh frame). The sleeve was introduced to produce a local reduction in the pressure and velocity of the gas during the brief period of combustion in the flame tube.

In nearly all experiments the fuel used was an approximate 7% mixture of propane in air.

Movies were taken with two cameras: one a Bell and Howell 70 with a speed of 80 frames per second, and the other an Eastman III high speed camera with speeds between 600 and 1,000 frames per second. The speed was determined from timing marks produced on the film by an oscillating light from an argon bulb inside the case of the camera. The frequency of the light was controlled with a Hewlett-Packard 205 AG audio-signal generator. The Eastman camera was modified so that a continuous loop of about 90 frames could be used, and an external shutter was used to limit the total duration of the series of exposures.

Procedure. Air and fuel are premixed in the proper ratio; then the mixture is introduced into the tube which is partially evacuated when the sleeve is not used, or which is thoroughly scavenged by flowing the mixture through it for several minutes. These procedures insure a rather uniform mixture free from moisture and other products of combustion left over from previous runs. All experiments are made with initial pressures of one atmosphere in the tube, and just before ignition a plate covering the bottom of the tube is removed so that the pressure in the tube will not build up to a dangerous level. Just before ignition takes place the shutter in front of the movie camera is opened and the film is exposed over a period of about a tenth of a second. The film, when developed, is viewed on a microfilm reading machine and the pictures are measured frame by frame. Figure 2 shows part of a series of pictures of the flame as it progresses down the tube. Frames 3, 5, and 7 clearly show the grid which was located four inches below the igniter. The black band across the tube at the bottom of frame 9 is a tube support.

A. Four-foot Pyrex Tube

Objectives and Experimental Results. The mean of the average flame speed in tubes which contained no grids was found to be 38 ± 6 ft./sec.

In the early experiments grids were pulled rapidly down the tube before ignition was started, in order that the flame could propagate into the turbulent wake of the grid. This arrangement was used in an

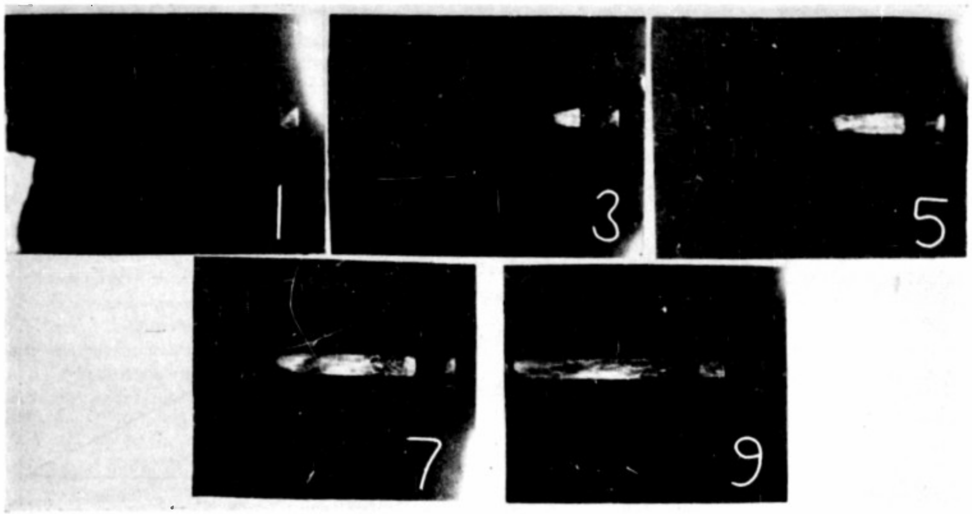

Figure 2. High speed motion pictures of a moving flame. The numbers in the lower right corners are frame numbers. Flame moving to left.

attempt to simulate the turbulence produced by the flow of the combustible mixture through the sharp edged intake valve bank in a pulse jet. These experiments indicated that flame speeds of the order of 100 ft./sec. could be developed behind the grid, but a new effect appeared when the flame passed down through the grid—very high flame speeds appeared. This observation led to a set of experiments using stationary grids.

Several general observations may be made on the appearance and velocity of flames in tubes containing stationary grids. A somewhat swirling combustion with flame speeds between 30 and 70 ft./sec. is frequently observed between the igniter and the grid. This flame then proceeds through the grid, exhibiting below that point a sharp acceleration and frequently attaining velocities of nearly 800 ft./sec. The burning in the rapidly moving flame front was never complete, inasmuch as after-burning was observed in regions where high velocities occurred, with little or no after-burning in those parts of the tube where the flame front moved slowly, and where presumably complete combustion occurred. Furthermore, the light intensity was greater in the flames with higher speeds. Indeed in many cases the light was insufficient to obtain pictures when the flame was above the grid, while below the grid the flame photographed clearly. The brightness in the less completely combusted region may be due to glowing carbon particles.

The early experiments were carried out with the No. 1 grid, using the Bell and Howell camera. It was found that the highest flame speeds were obtained when the grid was held about four inches from the igniter. Under these conditions an average speed over the four-foot length of tube was found to be about 320 ft./sec. This suggested that the flame accelerated below the grid, and this idea was confirmed when photographs were taken with the high speed camera.

Figure 3 depicts the results of a series with the No. 2 and No. 3 grids. Curve 1a gives the results obtained with the No. 2 grid four inches below the igniter. Curve 2 was obtained when grid No. 3 was two feet below the igniter. For this curve points are shown for only one of four shots, the data from which, however, follow the curve closely. It should be noted that the linear increase of velocity with distance indicated in curve 1a and 2, below the grid, means that the velocity v increases exponentially with the time t in this region.

That is

$$v = Ae^{\frac{t}{T}}$$

(with A and T constant).

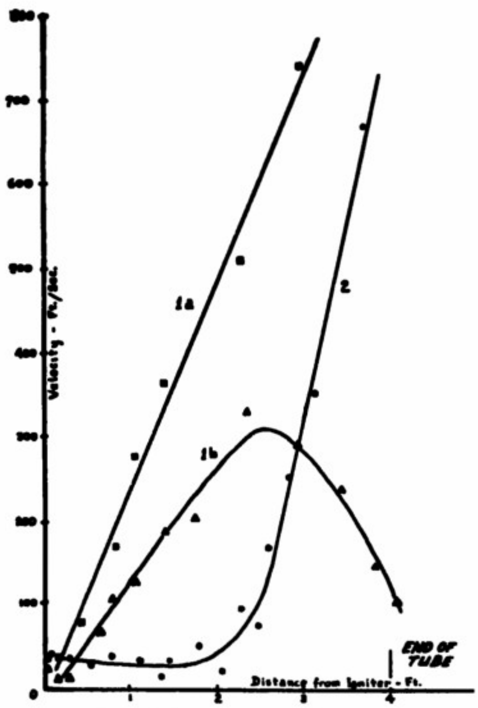

Figure 3. Flame speeds in a flame tube.

The time constant T, in the case of grid No. 1 is 4.0 ms., whereas its value for grid No. 2 is 2.1 ms.

It is possible that the difference in the slopes of curve 1a and 2 is a function of the grid. Further studies are necessary to determine the effect of grid design on flame speed and on acceleration below the grid. However, the results clearly indicate that the flame is suddenly and rapidly accelerated on passing through a turbulence-making grid, and then the flame speed increases exponentially with time.

Curve 1b illustrates one type of the non-reproducible results which occur now and then. In this experiment, in which grid No. 2 was used, the flame speed starts to increase as in curve 1a and then suddenly decreases. This is probably due to diffusion of the mixture out through the open end of the tube, owing to a delay of a few seconds between adding mixture and firing.

In the experiments with the wire helix which fitted snugly into the tube no measurable increase was observed over flame speeds in an open tube. With the helix of smaller diameter the flame speeds reached a value of 200 ft./sec. Presumably the mass motion of the gases along the centrally located helix set up a turbulence which accelerated the flame.

Pressure gauges are still in process of construction for the measurement of pressures in the tube. However, it is possible in one instance to estimate the pressure behind the grid from the observed acceleration of the grid when it was blown down the tube by the force of the explosion. Calculations gave a figure of four pounds per square inch excess pressure behind the No. 3 grid.

Remarks. In view of the experimental results described in the above paragraphs a few general remarks may be made concerning the mechanism of turbulent flame propagation. The grids in the path of the expanding gases create a turbulence, and it is probably this turbulence which induces the high speeds. Conceivably the flame front has a multiple needle shape with the points of needles lying on a mildly curved surface which looks like a flame front. The apparent shape of the flame front is somewhat curved, as may be seen in Figure 2, and this of course increases the observed speed over the "fundamental speed," that is, the local speed of the flame relative to the gas. Thus far no attempt has been made to measure the area of the flame front, but the ratio of this area to the cross section area of the tube, judging from the photographs in Figure 2, appears to be of the order of four. If fundamental flame speeds in non-turbulent gases are 10 ft./sec. or even 30 ft./sec., we can account for no more than 120 ft./sec. of the velocity on the basis of the simple curved front. For the several cases where the speed reached 750 ft./sec. it would seem that we cannot attribute the remaining 630 ft./sec. solely to mass transport caused by a pressure wave passing down the tube, because no such speeds were observed in the tube without grid. We are then led to postulate that grid-induced turbulence increases the flame velocity with respect to the tube by bringing fresh surfaces of gas into contact with the flame. The gas enclosed by these surfaces need not be burned completely (and indeed is not, as noted above). The fresh surface clusters may show themselves either as eddies or as jets or fingers which penetrate the unburned mixture and tend to propagate themselves forward locally to produce an effective flame front which moves with high velocity without being associated with a large cross-sectional average mass flow down the tube.

The use of fixed grids provides a means for controlling flame speeds and therefore may be of considerable importance in improving the performance of pulse jet motors. In particular, if flames can be made to propagate at speeds of more than 500 ft./sec., it may be possible to approximate in pulse jets conditions of combustion at constant volume, which may conceivably produce an improvement in the thrust of the motor. Thrust depends to a considerable extent on the relative phasing of pressure waves in the jet tube, and it is not certain that constant volume combustion is particularly effective in this connection.

B. Flame Tube With Expansion Chamber

Objectives and Experimental Results. The experiments discussed in (A) above suggested that (1) high speed flames are produced when a pressure build-up behind the grid leads to the development of jet-like motions through the grid, and (2) that average mass motion down the tube probably cannot contribute much to the effective flame speed. To check these conclusions the following experiments were performed in flame tubes with latex or tissue paper sections which were designed as pressure release devices.

Figures 4 and 5 show the results of most of the shots with the latex section tube. The vertical lines indicate position of the grid for each shot. Most of the curves are not drawn from the origin because the intensity of the flame near the origin was insufficient to produce an image on the film. Some of the curves are not drawn to the end of the tube for the same reason. The curves are drawn smoothly among points which in a few cases fall off these average curves by as much as 50 ft./sec.

Whenever the flame front was observable in the latex section, the velocity of the front was zero for a few frames. The flame filled the section, expanding it to the fullest diameter (and sometimes stretching the latex). It remained burning in this section before the front proceeded down the tube. This was observed in experiments 93 and 94.

A group of results are shown in Figure 4, in which conditions were apparently favorable to the production of a moderate amount of turbulence with consequent moderately high flame speeds. In all these cases either no grid was present in the tube or the grid was very near the end of the latex section.

When no grid was present in the tube, the highest velocities reached were about 250 ft./sec. The curves for experiments 81 and 94 illustrate this. These velocities are higher than those observed in

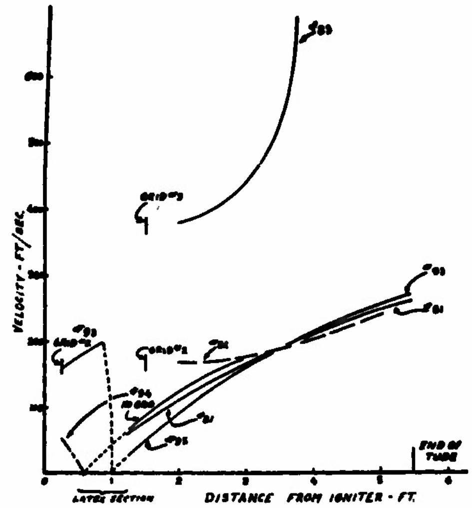

Figure 4. Flame speeds in tube with expansion chamber.

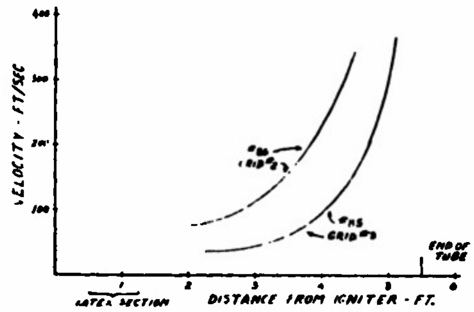

Figure 5. Flame speeds in tube with expansion chamber.

the straight tube without the latex section and may possibly be attributed to a slight turbulence set up by the expansion of the latex.

When the grid was near the latex section, either above or below it, the curves followed closely the behavior of the curves for no grid, as is seen from the curves of experiments 82 and 93. When the grid was above the latex the expansion possibly wiped out the turbulence due to the grid. If the grid was immediately below the latex, release of the pressure behind the grid may have slowed the gases proceeding downward through the grid so that little turbulence was produced. A notable exception in this group is experiment 83, where the results resemble very much those in the four-foot tube without an expansion chamber and with a similar grid position.

When the grid was about two feet below the latex section, as in the curves of experiments 85 and 86, shown in Figure 5, the curves resemble those of the tube without an expansion chamber and with the grid similarly placed. It may be that if it had been possible to follow the image of the flame front to the end of the tube, velocities of around 700 ft./sec. would have been observed. It would seem that the burning of the gas below the latex and above the grid permitted a pressure to develop which was not released immediately in the latex section, so that gases were forced through the grid much as they were in the straight tube.

Remarks. The results are confused by the superposition of the effect of the expanding and collapsing latex section, but our results thus far indicate that an effective release of pressure behind the grid, so that the gas is not forced through it, will decrease the turbulence to a point where very high flame front velocities are not observed.

A series of experiments is now in progress in which wet tissue paper is being used instead of latex. It has been found that the paper bursts very easily as the pressure front passes it, thus considerably reducing the pressure locally. Ideally, a tube of soap film would provide the clearest results, and efforts are being made in this direction. It is of particular interest in this connection to study the contributions to the flame speed due to average mass motion, by determining how a fast flame established in a 4-foot pyrex tube will continue to propagate into a tissue paper sleeve which forms an extension to the tube. In the pyrex tube the motion is confined effectively to one dimension, but in the sleeve, pressure and velocity propagate three dimensionally and therefore become rapidly attenuated with distance from the original center of the element. Thus mass motion parallel to the axis of the tube should be greatly reduced in the sleeve. Preliminary observations indicate that a flame with a speed of 500 ft./sec. near the end of the pyrex tube continues to propagate down into a two-foot tissue paper section at a rate which gradually drops to 150 ft./sec. Theory would lead one to expect a far greater decrease than this if the flame were being carried along mainly by mass flow.

IV. ONE-DIMENSIONALIZED RELATIONS FOR STATIONARY FLAMES IN TUBES

Observations on moving flames in pulse jets and in special flame tubes indicate that when suitable turbulent or eddy motion is present the following one-dimensionalized description is adequate.[4] The flame advances into the unburned gas with a speed as large as 200 or more ft./sec. relative to the gas, and the effective flame duration in each layer of gas is of the order of 10 to 20 ms., which corresponds to a flame region length of several feet along the gas in the tube. The actual burning takes place inhomogeneously and three dimensionally in a manner somewhat resembling the swirl in the wake of a ship's propellers. The detailed mathematical treatment of such swirling flow and combustion is beyond present techniques, and therefore a one-dimensionalized model is employed below.

[4] See Figure 6, which refers to a slightly expanding tube to stabilize the front.

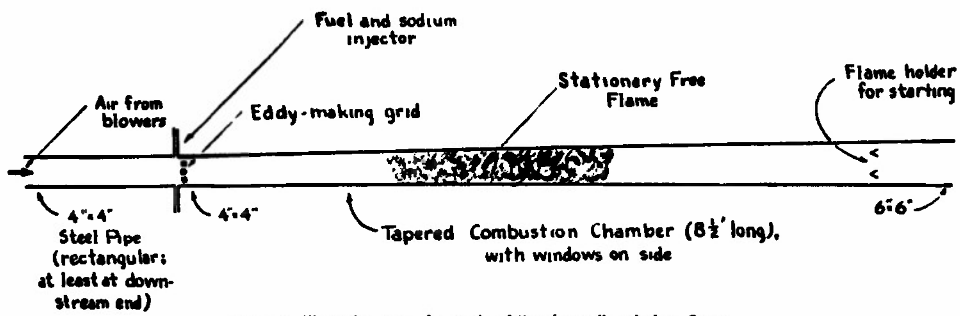

Figure 6. Tentative setup for study of "stationary" turbulent flames.

Suppose that the flow speed of combustible gas in a straight tube is adjusted until the free flame is stationary. The flow speed at the flame front then is equal to the flame speed f relative to the gas. Let Q = heat energy released per pound of gas during combustion (foot poundals per pound), U = internal energy per pound of gas, p = pressure (poundals per square foot,) τ = specific volume of gas (ft.^{3}/lb), V = flow speed (ft./sec.) and $W = V/\tau$ = mass flux of gas through a section one foot square (lb./ft.^{2} sec.). Using G_1 and G_2 for the respective values of a quantity G at the upstream and downstream ends of the flame region and using $G]_1^2 = G_2 - G_1$, we have the following basic equations:

(A) $Q = U]_1^2 + (p\tau)]_1^2 + \frac{1}{2}V^2]_1^2$ (enthalpy equation);

(B) $W = V/\tau$ (mass flux equation)

(C) $-p]_1^2 = (VW)]_1^2$ (momentum equation.)

W is a constant for the case of a straight tube, which is the case here. To obtain a rough estimate of the pressure distribution, let us assume we have a perfect gas, so that $U]_1^2 = \left.\frac{p\tau}{\gamma - 1}\right]_1^2$ which may be inserted in (A).

Here γ is the ratio of the specific heats of the gas and for purposes of estimation γ will be regarded as constant. Solving for $\Delta p = p_1 - p_2$ (the pressure drop through the flame region) in terms of γ, p_2 (the pressure at the downstream end of flame region), W (mass flux of gas), Q (the heat energy of combustion per pound of gas) and f, which is equal to V_1, the flow speed at the upstream end of the flame region, we have

(D) $$\Delta p = \sqrt{\left(\frac{\gamma p_2 - Wf}{\gamma - 1}\right)^2 + 2W^2Q} - \left(\frac{\gamma p_2 - Wf}{\gamma - 1}\right)$$

In a typical case of a stoichiometric gasoline-air mixture:

$\gamma \doteq 1.4$, $f < 200$ ft./sec., $W \doteq .08f$ lb./ft.^{2} sec.,

$Q \doteq \frac{1}{3} \times 10^8$ ft.^{2}/sec.^{2} (i.e. foot poundals per pound).

$p_2 \doteq 7 \times 10^4$ lb./ft. sec.^{2} (i.e. 1 atmosphere.)

In this case the last term under the square root in (D) is small compared with the first, and γp_2 is large compared with Wf; simple expansion then leads to the following good approximation:

(E) $$\frac{\Delta p}{p_2} = \frac{p_1 - p_2}{p_2} = \frac{1}{8}\left(\frac{f}{100}\right)^2$$

with the flame speed f measured in ft./sec. Correspondingly the number of horsepower required to drive the gas against this pressure difference Δp in a straight tube of cross section A (ft.^{2}), is

(F) $$\text{H.P.} = 1{,}600\left(\frac{f}{100}\right)^3 A \quad (\text{for } p_2 = 1 \text{ atmosphere}).$$

It is apparent from (F) that unless the flame speed f is considerably less than 100 ft./sec. the necessary horsepower is very large. Cutting down the area of cross section of the tube may help some, but cannot be carried too far as wall effects would be introduced which would dominate the phenomena.

V. TURBULENT DIFFUSION IN HIGH TEMPERATURE GASES

Theoretical. This phase of the work is primarily concerned with the study of the process of diffusion in turbulent flames, which is of importance in understanding turbulent exchange mechanisms which affect combustion. It is well known from experimental research that the influence of turbulence is very marked on the phenomenon of flame propagation. The flame propagation speed is in most instances noticeably increased, while the stability of the flame structure is altered to a significant extent. In order to obtain a thorough understanding of these phenomena it is essential to make experimental measurements in burning gases.

A theory of turbulent diffusion was developed essentially by G. I. Taylor and Th. v. Karman (cf. Goldstein, *Modern Developments in Fluid Dynamics*, Oxford, 1938). The results are primarily applicable to diffusion in fields of uniform isotropic turbulence. The essential features of the diffusion in such fields may be summarized as follows:

The rectangular components of velocity of a microscopic but not molecular particle in the fluid are taken to be $U + u$, $V + v$, $W + w$, where u, v, w are small fluctuations of the components about averages U, V, W taken over suitably small time or space intervals. The corresponding averages $\bar{u}$, $\bar{v}$, $\bar{w}$ of u, v, w are, of course, zero by definition. The field is characterized by an "intensity" which is a root mean square $\sqrt{\overline{u^2}}$ of u, (with $\overline{u^2} = \overline{v^2} = \overline{w^2}$ for isotropic turbulence) and by a "scale of turbulence" l, which may be defined in terms of correlation averages and which may be regarded as representing the average distance a particle can move in the direction x, say, with random velocity u, before u is reduced to zero. Then it is a result of the theory of turbulence that:

1. For time intervals which are small in comparison with the ratio of l_1 to $\sqrt{\overline{u^2}}$, the diffusing quantity spreads at a uniform rate proportional to the intensity $\sqrt{\overline{u^2}}$ and the rate is not dependent on the length l_1.

2. For time intervals which are large in comparison with the ratio of l_1 to $\sqrt{\overline{u^2}}$, the diffusing quantity ϕ spreads in accordance with the usual diffusion equation

$$\phi_t+U\phi_x+V\phi_y+W\phi_z = (D\phi_x)_x+(D\phi_y)_y+(D\phi_z)_z$$

where the coefficient of diffusion D is equal to $l_1\sqrt{\overline{u^2}}$.

3. For intermediate time intervals the diffusion is dependent on a function R_T which represents the correlation between the speed of a particle at any instant and the speed of the same particle after a time interval T. It is seen from the above that the experimental determination of $\sqrt{\overline{u^2}}$ and l_1 is of importance in the description of the diffusive character of turbulence. Under low temperature conditions the use of hot wire anemometry supplies in general the necessary information. However, the use of such apparatus is seriously limited in high temperature gases due to mechanical difficulties and to chemical effects. It has therefore been suggested to study the diffusion of particles from a point source located in a uniform field of isotropic turbulence. The task would then be to measure the extent of the diffusion with the help of a characteristic property of the particles, such as their charge, mass, color, etc. If a source of such particles is located in a gas stream we can determine the distribution of a particular property downstream from the source. According to our theoretical results we would expect a linear spread close to the source which could be measured in terms of the subtended angle. At a point downstream from the source where the correlation function R_T has fallen to zero the linear spread would change and show a more or less parabolic character. The diffusion of the property is not entirely due to turbulent agencies but is also brought about by molecular transfer mechanisms. It can easily be shown that the total subtended angle α which is measured is related to the turbulent diffusion angle α_t and the molecular diffusion angle α_o as follows:

$$\alpha^2 = \alpha_t^2 + \alpha_o^2$$

It is further possible to express the turbulent diffusion angle in terms of the turbulence level as follows:

$$\alpha_t = K\frac{\sqrt{\overline{u^2}}}{U} \quad (K\text{, a known universal constant})$$

It is therefore possible to determine the turbulence intensity $\sqrt{\overline{u^2}}$ from the subtended angle α if α_o is computed and if U is determined. The measure of the scale of turbulence can be obtained from the subtended angle and the distance of linear spread from the source, but a somewhat limited accuracy is anticipated.

The use of alkali salts to make the diffusion pattern visible in the flame was suggested by P. Chambré (Pasadena, 1946). The advantage of this method lies in the fact that the colored portion of the flame is readily distinguished by eye and photographic devices, whereas the use of other properties such as charge, mass, etc. would conceivably entail introduction of sampling probes into the flame which would alter the hydrodynamic character of the flow. The spectrum emitted by the metallic salts can also be adapted for temperature measurements in the flame by reversal line method or other comparison techniques. The determination of temperature is essential in applying suitable corrections to the molecular diffusion constants of the gas.

Experimental. A series of photographs of diffusion patterns from a glass bead held in a burner flame have been made. The glass bead was introduced into the flame on the end of a platinum wire, and photographs were taken at different gas velocities using four sizes of platinum wire, 19, 22, 26 and 28 B and S gauge. These observations were made to determine if the diameter of the wire influenced the measured subtended angle. It

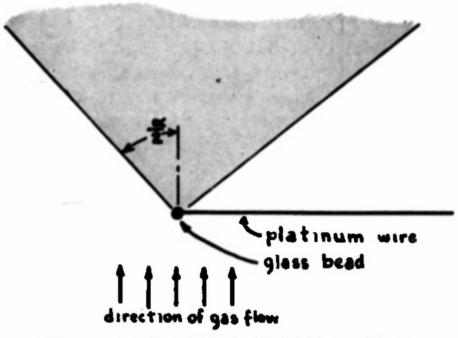

Figure 7. Angle of diffusion from a glass bead in a burner flame.

was found that within the precision of measurement no difference was observed for the four sizes of wire if half the subtended angle were measured on the side away from the wire holding the glass bead (see Fig. 7). When the measurement was made on that half of the angle near the wire the angle was a function of wire diameter, which is to be expected inasmuch as the gas flow is affected. The diffusion angle was therefore defined as twice the half-angle when measured away from the wire. A controlled source of air was not available at the time the measurements were made, but air openings on the burner were kept at a constant position for all experiments. A Fisher burner was used, and city gas was the fuel. Figure 8 shows the angle of diffusion versus rate of flow of fuel.

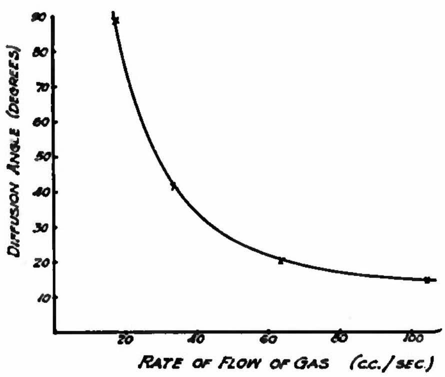

Figure 8. Diffusion angle versus rate of flow.

The root-mean-square velocity fluctuation $\sqrt{u^2}$ has commonly been measured with a hot wire anemometer, but this instrument unfortunately is not satisfactory in a hot flame. If U, the mean flow velocity, can be measured, $\sqrt{u^2}$ can be deduced. Hot wire anemometers must be discarded for this measurement for the same reason as above. Pitot tubes are not favorably regarded because of the disturbance which this rather gross instrument would introduce into the fluid stream. If this disadvantage could be overcome, it would be necessary to find for the tube a material that would not fuse shut when introduced into the flame.

A method which circumvents these difficulties but requires two measurements and some assumptions makes use of the equation

$$pU = mRT$$

p = pressure R = gas constant
m = mass rate of flow T = temperature

As is pointed out above, a knowledge of temperature is necessary for other aspects of the problem, and the sodium D-line reversal method is being considered for this measurement. A beginning in this direction has been made in the calibration of a tungsten-strip lamp for current versus temperature. Measurement of the pressure p would also be required, as well as measurement of m, along with the knowledge that m remained constant over the flame. Furthermore an analysis of the burned gases is required; or the assumption must be made that combustion is complete in the outer cone. The use of the gas constant R presupposes that the gases are ideal. This probably would not be an unreasonable assumption at near-atmospheric pressures and high temperatures.

A Bunsen or other standard type burner would not be satisfactory for the experiments if this method of measuring U were used because of the requirement of conservation of mass. Attempts were made to establish a flame with a planar front in a diverging tube in the hope that it might be possible to hold the flame sufficiently steady for the experiments. These attempts were not successful. Considerable oscillation was observed, probably because of excessive cooling of the pyrex tube, with consequent cooling of the gases and slowing of flame speed. Possibly insulation would improve the method, though the insulation would have to be of a special type to permit taking photographs through the wall. Another possible method is that of heating the tube electrically, but we are not hopeful of the success of this method, believing that a direct measurement of U would be more satisfactory.

Finally, a fourth method under consideration for measuring U is observation of the speed of an incandescent particle in the gas stream.

VI. THEORY OF NON-UNIFORM GASES

This phase of the work covers the mathematical theory of gaseous viscosity, thermal conduction, and diffusion for

(1) Systems without chemical reactions,

(2) Systems with chemical reactions.

In particular the study is concerned with investigations of non-Maxwellian distributions which are brought about by transfer processes in a gaseous system. The advent of jet propulsion and high speed missile design has raised questions of a rather basic nature in this respect. One might quote as examples the aerodynamic drag experienced by a missile in a rarefied atmosphere, where the molecular free mean path is large compared to the dimensions of the projectile. This problem has lately received some attention by H. S. Tsien (Pasadena, 1946). Another example is a statistical theory of the formation and structure of shock waves. The continuum theory as applied by R. Becker (*Zeitsch. f. Physik, 8*, 321-362, 1922) and others leads to shock wave thicknesses far below the applicability of the continuum theory. These are examples which fall roughly under class (1) above.

Problems of class (2) are not as well defined yet, but outstanding among them is an investigation of the non-equilibrium state in a gas brought about by very fast chemical reactions, involving inelastic collisions. Some of the mathematical apparatus pertaining to problems of class (1) has been summarized by S. Chapman and T. G. Cowling (*The Mathematical Theory of Non-Uniform Gases*, Cambridge). Problems falling under class (2) have not received very wide attention and a search of the literature in this field is being conducted. A group of statistical mechanics problems based on highly idealized models for molecules is being formulated and solutions are being attempted in order to develop mathematical techniques which may be useful in the treatment of more realistic models of combustion processes.

VII. SHOCK WAVE IGNITION

Purpose. Experiments are being conducted in which shock waves are to be used to produce ignition of gasoline-air mixtures in order to shed some light on the phenomena of reignition in a pulse jet. In addition it is expected that valuable information will be obtained concerning the general effect of shock waves on combustion in gases.

Background. Much information concerning the physical characteristics and method of production of shock waves is afforded in articles and reports by Rankine, Hugoniot, Jouquet, Taylor, and Becker, and more recently by Friedrichs, Payman, and Shepherd, and by the Princeton University shock wave group under Bleakney, in conjunction with NDRC and BuOrd contracts.

Particular reference is made to the experimental values and procedures of Payman [5] and Reynolds [6] and to the theoretical determination of the physical characteristics of non-linear wave motion by Courant and Friedrichs.[7]

To the writer's knowledge, there is no literature on the production of combustion (as contrasted with detonation) by shock waves.

Description of Apparatus. The essential features of the apparatus used for shock-ignition in experimentation at NYU are illustrated in Figure 1. The apparatus is divided into three sections, a compression chamber, 3 feet long, an expansion chamber, 5 feet long, and a combustion chamber which is 1 foot long. The sections are made of drawn brass pipe with an inside diameter of 1 inch and a wall thickness of 5/32 inch. Pressure is built up in the compression chamber by means of the compressed air tank in Figure 9.

Figure 9. Shock tube and associated equipment used in shock-ignition experiments.

The circular housing which separates the compression and expansion chamber is used as the mounting for a diaphragm. The particular advantage of this unit lies in the fact that it need only be pushed together for adequate sealing (up to 350 psi). This pressure seal is accomplished by hydraulic O-Rings, which are integral parts of the mechanism. This housing and a scotch tape diaphragm mounted in place are shown in Figure 10. When the diaphragm bursts, a disturbance which

[5] Payman and Shepherd, *Proc. Roy. Soc.*, A *1006*, 293-321, (1941).
[6] Reynolds, *NDRC Report A-192* (OSRD No. 1518).
[7] *Supersonic Flow and Shock Waves*, AMP, NDRC, AMG-NYU, 38.2R.

takes on the form of a plane shock wave is sent down the expansion chamber.

The combustion chamber and its allied elements are illustrated in Figure 11. The sliding plate is used to separate the gas-air mixture in the combustion chamber from the air at known temperature and pressure conditions in the expansion chamber. A fraction of a second before the diaphragm bursts, this plate is raised so that there is a free passage for the shock wave from the expansion chamber through a hole in the plate into the combustion chamber. This is done in order to present a relatively sharp interface between the gas-air mixture on the one hand and the air in the expansion chamber on the other at the time of arrival of the shock wave. The atomizer shown in the figure is used for spraying in the fuel, while the blower is used for scavenging after each trial. A heater coil, not shown in this illustration, is pictured near the center of Figure 9. This coil is used for raising the gas temperatures to the desired level.

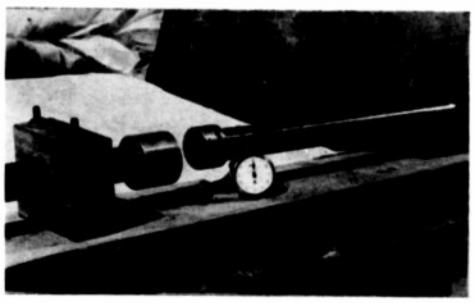

Figure 10. The housing for mounting the diaphragm (detail).

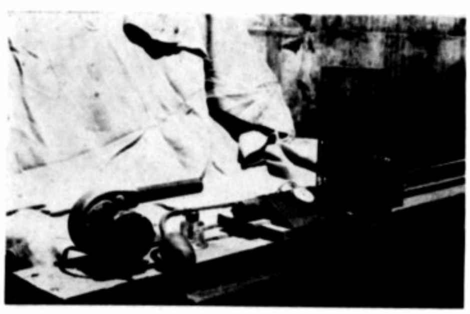

Figure 11. Combustion chamber and sliding plate with blower and atomizer.

Theory

A. *Temperature relationships in a shock wave.* If we use subscripts 1 and 2 to denote conditions ahead of and behind a shock front propagated down a tube, then (see e.g. Becker, *Ann. der Physik*, 1922):

$$\frac{v_1}{v_2} = \frac{\rho_2}{\rho_1} = \frac{(P_2/P_1)\,(\gamma+1)+(\gamma-1)}{(P_2/P_1)\,(\gamma-1)+(\gamma+1)}$$

$$\frac{T_2}{T_1} = \frac{P_2 v_2}{P_1 v_1} = \frac{(P_2/P_1)}{(v_1/v_2)}$$

where the symbols v, ρ, P and T denote velocities, densities, pressures, and temperatures (°K.) respectively, and γ denotes the ratio of the specific heats (C_p/C_v).

Let us calculate the temperature behind the shock wave in the following two cases:

(1) Let $P_2 = 4$ atmospheres, $P_1 = 1$ atmosphere, $T_1 = 293$°K. (room temperature). Then, by use of the above formulas we find that $T_2 = 469$°K. or 196°C.

(2) Let P_2 and P_1 be as in (1) but $T_1 = 600$°K. Then we find that $T_2 = 960$°K. or 687°C.

Therefore, with gas temperature initially $T_1 = 600$°K. throughout the entire tube, and assuming the ignition temperature of gasoline to be around 960°K. for such an experiment, an initial pressure in the compression chamber of the order of 16 atmospheres is required for ignition. This is based on the assumption that the effective pressure ratio in the shock wave is approximately one-fourth of the ratio of the pressures on the two sides of a diaphragm which is broken in order to generate a shock wave in the tube.

B. ***Rate of diffusion across an initial density discontinuity.*** At any instant after the sliding plate has been raised, in order to know the sharpness of the interface between the air in the expansion chamber and a stoichiometric mixture of gasoline in the compression chamber when both gases are at atmospheric pressure, it is necessary to solve the diffusion equation with an initial discontinuity in density between the two chambers.

Let $Q = -\Delta \frac{\delta \rho}{\delta x}$ be the rate of diffusion of the fuel in the fuel-air mixture across unit area in the positive x-direction. Here ρ is the density of the fuel in the mixture, and Δ is the diffusion constant. The diffusion equation is

$$\frac{\partial \rho}{\partial t} = -\frac{\partial Q}{\partial x}$$

or

$$\frac{1}{\Delta}\frac{\partial \rho}{\partial t} - \frac{\partial^2 \rho}{\partial x^2} = 0$$

The diffusion constant for small concentrations of alcohol into *non-turbulent* air at 40°C. is of the order of 0.14 cm.²/sec. At lower temperatures this is smaller, so a fair estimate for gasoline at room temperature might be 0.12 cm.²/sec.

Let us take the combustion chamber to the left of $x = 0$, and the expansion chamber to the right. Now the diffusion equation is to be solved subject to the initial conditions that at $t = 0$,

$\rho(x, 0) = \rho_o$ for $x < 0$ (initial density of the gasoline in the combustion chamber)

and

$\rho(x, 0) = 0$, for $x > 0$

and for $t > 0$, we have for the boundary conditions

$$\rho(-\infty, t) = \rho_o$$
$$\rho(\infty, t) = 0$$

The solution of this problem is

$$\rho(x, t) = \frac{\rho_o}{\sqrt{2\pi}} \int_{\frac{x}{\sqrt{2t\Delta}}}^{\infty} e^{-\frac{y^2}{2}} dy$$

At $x = 0.635$ cm. $= 0.25$ in., we have

$$\frac{\rho}{\rho_o} = \frac{1}{\sqrt{2\pi}} \int_{\frac{1.3}{\sqrt{t}}}^{\infty} e^{-\frac{y^2}{2}} dy$$

or

$$\frac{\rho}{\rho_o} \times 100 = \left[\frac{1}{2} - \frac{1}{\sqrt{2\pi}} \int_{0}^{\frac{1.3}{\sqrt{t}}} e^{-\frac{y^2}{2}} dy\right] \times 100$$

as the per cent of fuel (in terms of the initial density in the combustion chamber) ¼ of an inch to the right of the original interface at any time t.

Table 1 gives a list of values of this per cent at various times t.

TABLE 1

Time (sec.)	Fuel Percentage at x = 0.25 inch
0	0.00
0.16	0.06
0.25	0.47
0.49	3.16
1.00	9.68
4.00	25.78

Thus, if the shock wave arrives at the interface one second after removing the sliding plate, the mixture ¼ of an inch from the original interface has changed by only 10% of the mixture originally in the combustion chamber (on the assumption that non-turbulent diffusion is involved).

Procedures and Results. The experiments performed thus far have been mostly of a qualitative nature and though ignition has not as yet been obtained, some interesting results are available.

In order to determine the proper fuel-air mixture the atomizer pictured in Figure 11 was used to spray gasoline into the compression chamber. The tube was then sealed and the gasoline heated until complete vaporization took place. A spark plug which was mounted inside the tube was then sparked. In this manner we were able to determine the optimum number of pumps of the atomizer bulb needed for a proper mixture.

A series of experiments is under way to see if shock ignition as proposed is possible. In doing this, scotch tape diaphragms are used. These diaphragms can be made the proper thickness so that they will burst at previously determined pressures. Having a given fuel mixture and compression chamber pressure, the next controllable parameter is the temperature.

With the above theoretical results in mind it was decided to vary the temperature of the gas from about 285°K. up to approximately 600°K. at 4 atmospheres shock pressure. At the present time wall temperatures of about 400°K. have been reached.

Future Proposals. Future experiments will be concerned with raising the temperature of the gas in the combustion chamber to a sufficiently high level so as to induce ignition through the use of shock waves. After ignition has been obtained, controlled experiments are being planned in which more quantitative measures of the parameters of temperature, pressure, density, and humidity will be carried out in all three sections of the tube. In the way of theoretical investigations, it is hoped that once some figures are available concerning the various parameters involved, it will be possible to formulate a theory of what occurs during reignition in a pulse jet.

VIII. MEASUREMENT OF THERMAL PROPERTIES OF STEEL AT HIGH RATES OF CHANGE OF TEMPERATURE

Purpose. In the complete description of the operation of a liquid rocket or pulsating jet, account must be taken of the transfer and conduction of energy from the gases in the motor into and through its walls. The solution of this heat flow problem thus requires a knowledge of the behavior of the thermal conductivity and specific heat of the wall material under operating conditions. When a rocket is fired, the high velocity hot gases rapidly heat the steel walls of the rocket. At any instant the temperature distribution and consequently the wall strength depends on the previous flow of heat in the wall. This flow depends on the thermal parameters of the wall material as well as on the heat transfer from the hot gases to the wall. Consequently experiments have been designed for the measurement of the thermal parameters of the walls for different high and low rates of change of temperature. In these experiments steel specimens are to be heated by passing an electric current through them.

Background. In the *Second Report of the Alloys Committee to the Iron & Steel Industry* in 1937, some accurate experimental work is reported on the specific heat of steels. This fairly exhaustive program was carried out under the direction of Griffiths. Steels with carbon content ranging from 0.06% to 1.22% were used. The work was done essentially under static conditions, however, which posed few of the problems met with in rapid heating. For a rate of change of temperature of 1,000°C. per second, an adiabatic container is almost impossible to realize, although calculation could take into account radiation losses. This classical work shows that for each specimen used, a very sharp rise of the specific heat occurs at about 730°C. For instance, steel of 0.23% carbon has a specific heat of 0.2 at 700°C. and 1.7 at 730°C. The "width" of the peak is about 10°, and save for some subsidiary peaks, the curve settles down to 0.15 for higher temperatures. It is of interest to note that this latter value is the same for all specimens used.

In the same report, values of the thermal expansion, $\left(\frac{L_T - L_0}{L_0}\right)$ are given. The curve of $\left(\frac{L_t - L_0}{L_0}\right)$ against temperature rises linearly up to 730°C., at which point it turns and is linear with negative slope to about 810°C. Here it turns again and has a positive slope parallel to the initial slope.

In *Science Reports* (Tohoku Imperial University, First Series, Vol. VI) the variation of thermal conductivity with temperature for several carbon steels is presented. Like the thermal expansion, the conductivity also shows a change in the vicinity of 730°C.

If one neglects losses by radiation for the moment, then an idea of the current required to heat a specimen can be obtained.

Consider a rod of radius r, length l, electrical resistivity ρ, specific heat s, and density d. Let its instantaneous rate of change of temperature be $\dot{T}$, and let there be a current I flowing through it. Then the power equation is

$$I^2 \times \frac{\rho l}{\pi r^2} = J \pi r^2 l s d \dot{T}$$

where J is the mechanical equivalent of heat. So that

$$I = \pi r^2 \sqrt{\frac{s d \dot{T} J}{\rho}},$$

and if

$l = 20$ cm, $r = 1.5$ mm, $\rho = 20 \times 10^{-6}$ ohm-cm,
$s = 0.11$ cal/gm, $d = 7.7$ gm/cc,
$T_R = 400°$K/sec, $J = 4.18$ joules/cal,

then $I = 590$ amps.

The resistance of this rod is

$$R = \frac{\rho l}{\pi r^2} = 5.7 \times 10^{-3} \text{ ohms.}$$

If the internal resistance of a 6-volt lead storage is taken to be 1/50 ohm then, using 4 cells in a series-parallel combination, we get a 12-volt source having 1/50 ohm internal resistance. This will give a current

$$I = \frac{12}{0.02 + 0.006} = 460 \text{ amps.}$$

This is less than the current required for a heating rate of 400°/sec., but will be sufficient for a preliminary trial.

Calculation shows that if the heating is done at a rate of 100°/sec., the losses by radiation become serious at 300° C. For such rates a shield would be necessary.

Experimental Setup. In order to compare the effect of rate of change of temperature on the specific heat, with the values given in the *Second Report of the Alloys Committee*, a carbon steel had to be found which would be as similar to the original specimens as possible. AISI C1040 has about 0.40% carbon, and 0.60% manganese, which is the best approximation that could be found. Specimens of this steel have been annealed at 950°C., as were the British steels.

The piece of steel to be used is about 3.0 mm. in diameter, and 20 cm. long. It will be mounted within an evacuated glass tube, with heavy conductors passing in to carry the heating current. The glass tube, about 30 cm. long, will be sealed at both ends with rubber stoppers, through which the heavy cylindrical rods pass. The rods will be drilled at one end so that one end of the steel specimen can fit in and be tightened for good electrical contact.

A platinum platinum-rhodium thermocouple will be attached at the middle of the steel rod to measure the temperature. The thermocouple elements are 0.002 inch in diameter and should not have enough heat capacity to cause serious lag. The voltage from the couple will feed into an amplifier and finally appear on the screen of an oscilloscope. A camera will be mounted in front of the screen, with the shutter left open. When the main switch is closed, the 12 volts are connected across the specimen and a linear sweep circuit is triggered.

Separate leads will pick up the voltage across the specimen and the current through it, and these quantities also will be amplified and displayed upon a screen.

A timing pip superimposed upon the oscilloscope scan will be used to record the time.

The record obtained in this way will actually be a curve of total heat vs. temperature. Information regarding the specific heat, requires a differentiation of this curve.

Results. The apparatus described in the foregoing is under construction, and no records have yet been obtained.

Future Work. The problem of measuring the thermal conductivity as a function of the rate of change of temperature seems to be far more difficult. As yet no definite method of solution has been settled upon.

IX. NON-LINEAR HEAT CONDUCTION

Introduction. In designing rockets and pulse jets it is desirable to know the transient temperature conditions in the walls during and after firing so as to be able to calculate thermal stresses, probable amount of melting, and so forth. Ordinary theoretical treatments which assume constant heat conductivity and capacity of the metal may be seriously in error since the actual variation of these quantities is quite large (over 100%) for the range of temperatures encountered (as much as 800°C.). Hence it has seemed desirable to investigate the non-linear partial differential equation which governs the flow of heat, taking account of the temperature dependence in the thermal conductivity and capacity.

Previous theoretical treatments have been confined to numerical calculations of specific cases, replacing the partial differential equation by a difference equation or system of ordinary differential equations. Depending on facilities, results may be obtained graphically (e.g., by the Schmidt method), or by direct calculation, or with the aid of a differential analyzer or analog computer. Such methods are well known for the case of constant thermal quantities (i.e., when the equation is linear); their adaptation to the case of variable thermal quantities is in principle quite straightforward, but the essential difficulty that characterizes all numerical methods remains; namely, only specific cases may be calculated, so that statements of a general nature as to the effect of variations in the end-conditions, geometry, etc., on the solution are very difficult to make. It is of course too much to hope for to find an exact analytic solution of the non-linear partial differential equation for arbitrary boundary conditions; it is possible, however, to obtain in analytic form certain results.

Analytic treatment. We consider the one-dimensional flow of heat through a slab of thickness L (since the walls are relatively thin, this is an adequate approximation). Letting $T(X, \theta)$ = temperature at distance X from the inner surface at time θ, $K(T)$ = conductivity, $S(T)$ = specific heat times the density, we have the equation for T.

$$(1) \quad \frac{\partial}{\partial X}\left(K\frac{\partial T}{\partial X}\right) = S\frac{\partial T}{\partial \theta} \qquad \begin{cases} 0 \leqq X \leqq L \\ \theta \geqq 0 \end{cases}$$

Making the substitutions

$$Q = \int_{T_0}^{T} \frac{K\,dT}{K(T_0)}, \quad T_0 = \text{conveniently chosen mean } T;$$

$$\alpha = \frac{K(T)S(T_0)}{K(T_0)S(T)};$$

$$x = \pi X/L, \qquad t = K(T_0)\theta\pi^2/S(T_0)L^2;$$

equation (1) now reduces to

$$(2) \qquad \alpha\frac{\partial^2 Q}{\partial x^2} = \frac{\partial Q}{\partial t}.$$

(It will be noticed that Q is a weighted temperature; e.g. if K = constant = $K(T_0)$, $Q = T - T_0$.) The typical behavior of α, for temperatures below critical values associated with a change of state (in steel the lowest such temperature is around 700–800°C.), is indicated in Figure 12. Two types of result are obtained: (i) particular solutions for special forms assumed for α, (ii) a perturbation series development for Q in powers of ϵ, where, e.g., ϵ is some mean $(\alpha - 1)$.

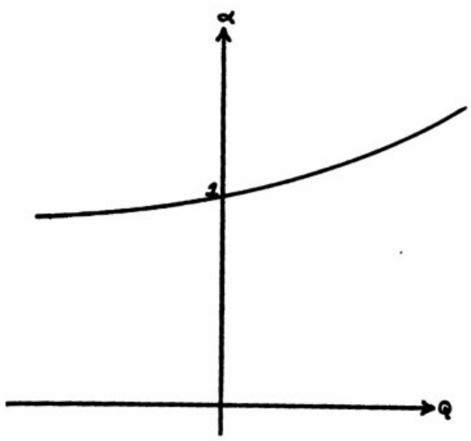

Figure 12. Typical behavior of α for temperatures below critical values.

(i) *Particular solutions.* a) Suppose A and B are determined so that α may be approximated by

$$\alpha = Ae^{BQ}$$

Then, we assume $Q = f(x) + g(t)$, substitute in (2), separate variables, and obtain

$$Ae^{Bf} f'' = e^{-Bg} g' = \text{const.}$$

These ordinary differential equations may be solved and furnish the particular solution:

$$Q = \frac{1}{B} \log \frac{\cosh^2(ax+b)}{2Aa^2(c-t)}$$

where a, b, and c are arbitrary constants which may be chosen to approximate some types of initial or boundary conditions.

(b) We might alternatively suppose that A, B and n are determined so as to approximate α by

$$\alpha = A(Q - B)^n$$

Then, if we assume $Q - B = f(x)\,g(t)$, (2) will again separate. In particular for $n = 1$, i.e., a *linear* approximation to α, we obtain

$$Q - B = \frac{x^2 + ax + b}{2A(c-t)}$$

For $n = 2$, i.e., a *quadratic* approximation to α, we obtain

$$Q - B = \frac{b \exp y^2(x)}{\sqrt{A\pi}\,(c-t)}$$

where

$$\frac{x-a}{b} = \frac{2}{\sqrt{\pi}} \int_0^{y(x)} e^{u^2}\,du$$

(ii) *Perturbation series.* Suppose that in a certain practical case we can approximate α by the form $\alpha = 1 + \epsilon Q$ (ϵ is a small constant).

Assuming that

$$(3) \quad Q = q^{(0)}(x,t) + \epsilon\, q^{(1)}(x,t) + \ldots.$$

so that

$$(4) \quad \alpha = 1 + \epsilon\, q^{(0)} + (\text{terms in } \epsilon^2 \text{ etc.}) \ldots,$$

and that initial and boundary conditions are given in the form $Q(0, t) = f_1(t)$, $Q(\pi, t) = f_2(t)$, $Q(x, 0) = f_3(x)$, we substitute (3) and (4) into (2), equate like powers of ϵ, and obtain a succession of boundary value problems as follows:

$$(\epsilon^{(0)}) \qquad \frac{\partial^2 q^{(0)}}{\partial x^2} = \frac{\partial q^{(0)}}{\partial t}, \quad \begin{cases} q^{(0)}(o,t) = f_1(t) \\ q^{(0)}(\pi,t) = f_2(t), \\ q^{(0)}(x,o) = f_3(x) \end{cases}$$

$$(\epsilon^{(1)}) \qquad \frac{\partial^2 q^{(1)}}{\partial x^2} = \frac{\partial q^{(1)}}{\partial t} - \frac{\partial^2 q^{(0)}}{\partial x^2} \; \frac{\partial q^{(0)}}{\partial t}, \; q^{(1)}(o,t) = q^{(1)}(\pi,t) = q^{(1)}(x,o) = 0;$$

etc.

The solution of $(\epsilon^{(0)})$ is well known,

$$q^{(0)} = \frac{2}{\pi} \sum_{1}^{\infty} e^{-n^2 t} \sin nx \left\{ \int_{o}^{\pi} f_3(x) \sin nx \, dx + n \int_{o}^{t} e^{n^2 \lambda} [f_1(\lambda) - (-1)^n f_2(\lambda)] \, d\lambda \right\}.$$

The solution of $(\epsilon^{(1)})$ may be obtained by the Laplace Transform; it is

$$(5) \qquad q^{(1)} = \frac{-2}{\pi} \int_{o}^{\pi} \int_{o}^{t} \frac{\partial q^{(0)}(x',\lambda)}{\partial \lambda} \frac{\partial^2}{\partial x'^2} q^{(0)}(x',\lambda) \sum_{K=1}^{\infty} e^{-K^2(t-\lambda)} \sin Kx \sin Kx' \, d\lambda dx'$$

$$= \sum_{K=1}^{\infty} a_k(t) \sin Kx$$

The coefficients $a_k(t)$ may be evaluated explicitly in terms of the functions $f_1(t)$, $f_2(t)$, $f_3(t)$; or it may be more convenient to calculate (5) directly.

It is planned to apply the above results to numerical cases, to extend the results in (ii) to the case of prescribed heat inflow at the boundaries, and to give estimates of the error involved in ignoring the variation of the thermal coefficients.

X. CONSTRUCTION AND TESTING OF SMALL PULSE JETS

Purpose. Pulse jets have been constructed to serve three purposes: (1) to test simply and directly the effect of various combinations of combustion chamber and tail pipe lengths on thrust, fuel consumption, and cyclic firing rate, with a view towards the checking of theories of pulse jets and towards the designing of multi-tube motors, (2) to provide a way to observe visually and photographically the combustion process, and (3) to provide a source suitable for testing temperature, pressure, and other instrumentation to be employed later on large pulse jets.

History. Though many small pulse jets have been built in the past by other experimenters, no description has been found of pulse jets specifically designed to serve the purposes listed above. Some experiments were conducted at Wright Field and elsewhere in which photographic records and optical measurements were made through windows in pulse jets, but this did not furnish sufficient data for a complete analysis to be made.

Description of Apparatus. So far, to serve these four purposes, six small pulse jets and several pieces of accessory equipment have been constructed.

The first pulse jet (SQUID Mark I) was constructed of steel tube and was designed to permit investigation of the effects of both combustion chamber size and tail pipe length on pulse jet performance.

The second pulse jet (SQUID Mark II) was a transparent pulse jet constructed of pyrex tube to see whether completely transparent jet tubes were feasible.

The remaining four pulse jets (SQUID Mark III Series) have transparent side walls and were constructed after tests on the SQUID Mark II indicated that transparent pulse jets might be practicable. The change from pyrex tube to pyrex plate was made because we believed that optical distortion would be reduced and also that it would be less difficult to construct jets of different geometries.

The third, fourth, and fifth pulse jets (SQUID Mark III Model O, Casts 1, 2, and 3) were made

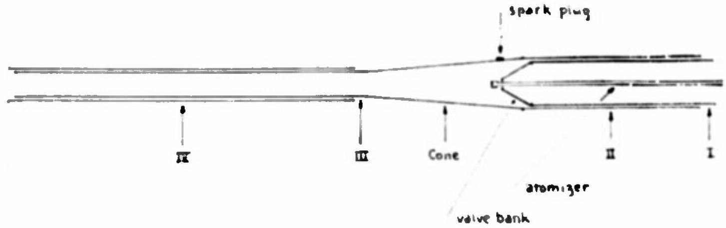

Figure 13. Cross section of SQUID Mark I.

of plaster-of-paris and have been tested with both soda glass and pyrex glass walls.

The sixth pulse jet (SQUID Mark III Model I) though made of transite (a type of asbestos board) instead of plaster-of-paris, is otherwise similar to the rest of the Mark III Series.

The accessory equipment that is used with these jets is described under Subsection A (Steel Tube Jet) and Subsection B (Transparent Jets).

A. *Steel Tube Pulse Jets (Mark I) and Accessory Equipment*

1. *Accessory Equipment.* The accessories used with the steel tube pulse jet are (a) an ignition system, (b) a fuel delivery system, (c) a thrust stand, and (d) a blower installation.

(a) The ignition system consists of a six-volt battery connected to a Ford spark coil. The coil is grounded to the pulse jet, and the high voltage lead is connected to the spark plug.

(b) The fuel delivery system is built around a variable capacity (3 to 150 pounds per hour) gasoline atomizer developed by the Combustion Equipment Division of Todd Shipyards Corporation for turbo-jet engines. Basically it resembles the marine return-flow oil burner, and its greatest advantage is complete atomization even when ejecting only three pounds of fuel per hour. The fuel is placed in a tank and the required 300 psi delivery pressure is obtained by pressurizing the tank with nitrogen from a nitrogen cylinder. The tank pressure is maintained at 300 pounds by a regulator valve on the nitrogen cylinder. All the hose connections are of synthetic rubber and a valve in the return-flow line is used to control the amount of fuel ejected. The fuel that is not ejected by the atomizer is collected in another tank.

(c) The thrust stand consists of three parts, the front support, the rear support, and the base. The front support is a welded structure that can rock on pivots in the base. The front end of the jet is pivoted, in turn, on the front support, and the rear end is supported by a rocker arm. Thrust is measured by a spring scale attached to the front support but, since preliminary calculations indicated it was not needed, no damping mechanism was installed.

(d) The blower used to provide ram air is a variable speed centrifugal fan that has a maximum capacity of about 250 cubic feet per minute.

2. *Description of Steel Tube Pulse Jet (Mark I).* The Mark I is constructed of steel tube and sheet metal. Its general layout is shown in Figure 13. To the front inner tube are attached (a) the lugs that fit in the front support of the test stand and (b) the valve bank which is shown in Figure 14. The tip of the atomizer projects through a hole in the center of the valve bank whose valve leaves are made of .005 steel strip.

A variable size combustion chamber is obtained by attaching the valve bank to the rear end of the front inner tube (Tube I), which is slid into the front outer tube (Tube II). The tail pipe is varied in length by sliding the rear outer tube (Tube IV) back and forth over the tail pipe (Tube III).

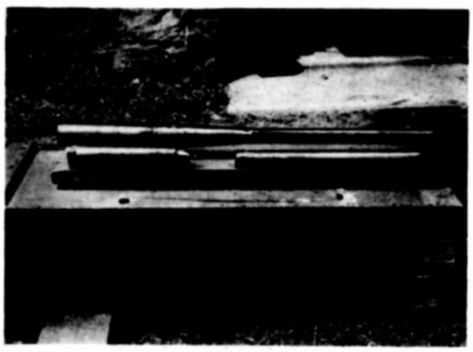

Figure 14. Steel tube pulse jet (Mark I) disassembled.

B. *Transparent Pulse Jets and Accessory Equipment*

All of these pulse jets have been based on and use parts of the model aircraft jet engine made by Minijet Motors, Pasadena, California. This jet has a four-sided pyramidal valve bank. Its fuel delivery system is unusual because the pressure rise that occurs during each combustion cycle is used to force the gasoline up from the sealed tank and to eject it from the atomizer located ahead of the valve bank.

We have used the Minijet engine parts from the air intake back to and including the valve bank, in order to avoid the necessity of designing and constructing our own valve banks and fuel delivery systems until our investigations indicated that a different design was desirable.

1. ***Accessory Equipment for Transparent Jets.*** In addition to the ignition system and blower used with the steel tube jet, a hand tire pump, the gas tank recommended for the Minijet, and the Minijet fuel injection system described above are used.

2. ***Pyrex Tube Pulse Jet (Mark II).*** A reproduction of the Minijet from the valve bank to the rear end of the tail pipe was blown from pyrex tubing one inch in diameter. The spark plug was cemented into a small glass tube projecting upward from the upper surface of the combustion chamber. This assembly was installed concentrically in a 4" diameter cooling tube made of sheet acetate. After fibre end plates were attached so that the space between the tubes could be used as a water jacket, the front section of a Minijet was cemented on. A sketch of Mark II is shown in Figure 15.

3. ***Pulse Jets with Transparent Walls (Mark III Series).*** The Mark III pulse jet, shown in Figure 16, was made with pyrex plate glass side walls and plaster-of-paris upper and lower walls. Materials other than plaster-of-paris have been considered, among them transite, sheet metal, moldable fire brick, and portland cement. All except the last of these seem to offer fabrication problems that we wish to avoid if possible.

The mold used to cast the plaster parts is shaped to give a pulse jet of approximately the same length as the Minijet, and with the same cross sectional area at corresponding points. Two brass rods through the plaster, one insulated from the plaster cast by a sleeve of glass tubing, served as a spark plug. The inner ends of the rods were bent over to provide the proper spark gap. In the latest tests the air-cooled glass plate side wall has been seated on gasket material instead of directly on the plaster, and four more C-clamps have been used to hold the plate in place instead of as shown in Figure 16.

The upper and lower walls of the transite jet (Mark III Model 1) were built of transite strips. These were used in place of the plaster-of-paris sections of the Mark III Model 0 jets.

Test Procedure. For photographic recording of a test, the pulse jet is set up as in Figure 16. A Hi-Speed Eastman III camera is placed to view the jet from the side. In the latest tests, a timing device that aids calculation of both the scale-factor and the speed of the film is mounted just above the jet in the field of view of the camera. The blower is located several feet ahead of the air intake of the pulse jet and a cloth duct leads the air to the intake.

After the camera is loaded the blower is brought up to speed and the timing device is started. The

Figure 15. Sketch of SQUID Mark II.

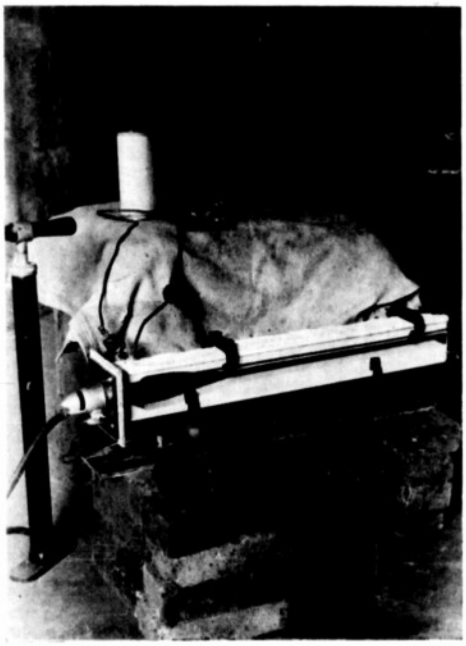

Figure 16. Transparent-walled pulse jet (Mark III Model O, Cast 2), set up for a test run.

pulse jet itself is started by the tire pump, the blower being used merely to aid the jet to draw in the fresh mixture. The spark is usually operated intermittently and is shut off completely when the jet begins to run continuously. As soon as the jet is resonating the camera motor is turned on to make the record.

For visual observation and optical measurements the same procedure is followed with the omission of the film speed device and the camera.

Results

A. *Steel Tube Pulse Jet.* No useful data have as yet been obtained from the Mark I pulse jet since the only run made was with an oscillating blower, and the jet muttered rather than resonated.

B. *Transparent Jets. Mark II.* Although only rather faint photographic records were made with the Mark II due to the use of a too high frame speed with the high speed camera, the operation of the jet was sufficiently good to indicate that improved models would perform satisfactorily. The tubing cracked after only a few runs due, apparently, to stresses set up in forming the glass and in assembling the jet. It was partly for this reason that the Mark III jets were designed with plate glass walls.

Mark III. Tests have been run on Mark III jets with soda glass walls which cracked soon after firing started. Better clamping and sealing do not seem to provide sufficient improvement in durability to make soda glass a suitable wall material for air-cooled transparent-walled pulse jets. Pyrex glass, however, requires considerable time for delivery.

The Mark III Model 1 jet with transite upper and lower surfaces has not been tested sufficiently to allow any conclusion to be drawn as to suitability of this material.

During the last tests made before this report was written, runs of several seconds duration at true resonance were obtained. Subsequent examination showed that sealing was still not quite complete, and since previous experience with the original Minijet indicated that complete sealing is essential, it is expected that in the next tests resonant running for ten to fifteen seconds will be obtained.

In Section XI a brief analysis of photographic data obtained from a test run of a Mark III type jet will be found.

Future Proposals. Since these transparent-walled pulse jets have run successfully for ten seconds or more at a time, an extensive program of construction and testing of transparent-walled pulse jets of the same and other designs has been drawn up. Concurrently, attempts will be made to obtain closer control and more accurate measurement of the variables involved in pulse jet combustion.

XI. PRELIMINARY OBSERVATIONS OF FLAME MOTIONS IN A PULSE JET

Introduction. In testing the glass-walled jet, Mark III, as described in Section X of this report, a high-speed photographic record of the flame motions in the interior of the jet has been obtained. This was done while the jet was operating intermittently, that is, resonating for a few seconds at a time, and the spark was running continuously. Consequently the photographic record, the only one obtained so far on this kind of jet, may not be a typical one, because the observed flame motion was not truly unperturbed. In fact, it was recorded only in the last two or three "cycles" before dying away. Nevertheless, the few interpretable frames on the film show interesting features which may be significant in the light of further observation. Very recent motion pictures confirm most of these features for a truly resonating run.

General Features of the Record. An examination of the film shows the following sequence of events. First a knot of flame or "flambeau" is propagated through the tail pipe from the combustion chamber. This flambeau is from one to two inches in length and is preceded in some of the frames by an almost transparent region of burning. After a brief interval of no burning there appears a marked band of flame, roughly six inches long, which follows perhaps four inches behind the flambeau. After another brief interval of no burning, a second flambeau similar in size to the first and presumably corresponding to the following cycle, is propagated through the tail pipe about three inches behind the flame band. A faint suggestion of burning occurs later, and then several frames afterward a third flambeau associated with some later cycle moves down the tube (at a higher speed than the first two however). In two frames, both the first and cond flambeaux as well as the flame band are visible. Figure 17 shows this situation as it appears in frame 10.

Analysis of the Record. The film speed was roughly 1,000 frames/second. This, combined with measurements of the rather vague outline of the interior of the jet motor, furnished space and time scale factors so that the absolute motions could be plotted. This is done in the graphs of Figure 18. The curves marked A and C show the observed motion of the flambeaux, and the shaded region B denotes the position and size of the flame band at each instant. On the same figure is shown drawn to scale a sketch of the outline of the interior of the jet, so that as the flames move through the jet it is possible to trace the effect of the changing cross section of the jet-interior on them. In particular, it is seen that the length of the flame band increases from 3.5 inches to about 6.4 inches as the band moves into the tail pipe from the combustion chamber. It then retains this length as it moves down the tube.

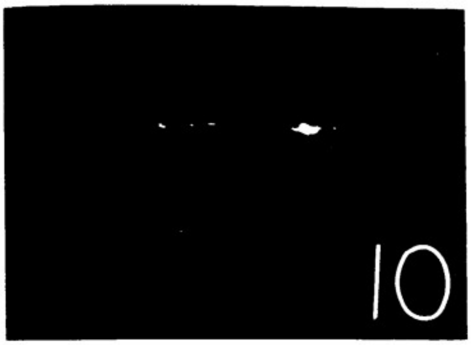

Figure 17. Flambeaux and flame-band in a pulse jet.

There are several other striking characteristics of these motions. First, note that the two flambeaux and the flame band speed through the system with very nearly the same velocity at any given instant, and with nearly the same average velocity of 175 feet/second over their entire paths. Moreover the velocity of each of these flaming regions, averaged over about 3.5 milliseconds (or frames), shows a

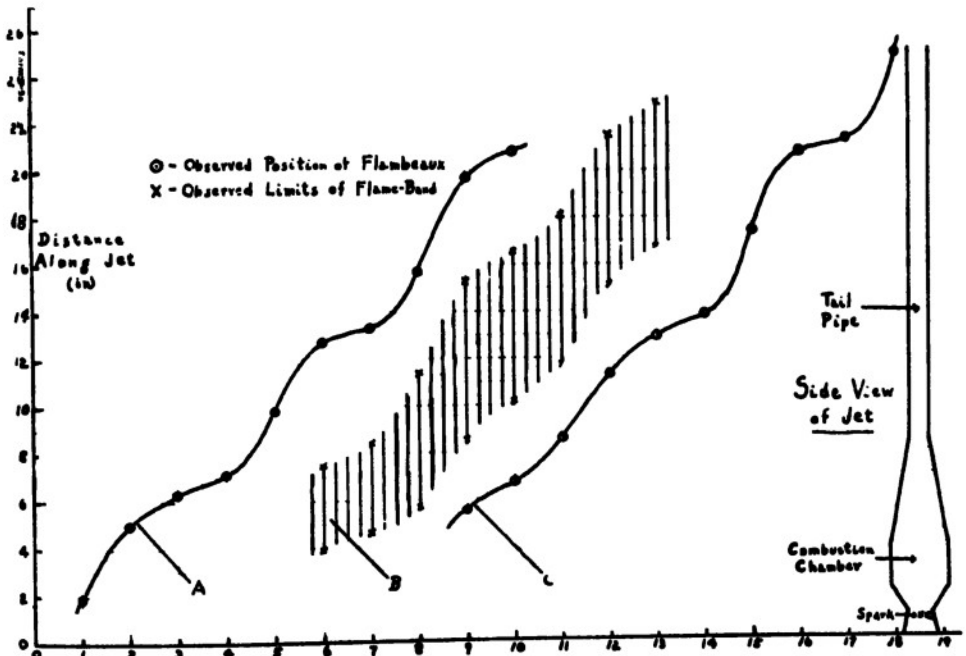

Figure 18. Motion of flame in a jet "cycle."

gradual increase as they move through the tail pipe. This is particularly noticeable in the case of flambeau C which shoots out the rear of the tail pipe at a terrific velocity.

Superimposed on these gradually accelerated motions is a rapidly fluctuating motion, with a definite period of about 3⅓ milliseconds, or frequency of 300 cycles/second. If the time interval of 6.5 milliseconds between the appearances of the flambeaux at corresponding points be taken to correspond to the fundamental resonating period of the jet, its resonant frequency is 154 cycles/second, or nearly one-half that of the fluctuating motion. This may be a coincidence, but it suggests that a cause of the velocity fluctuations may be found in pressure waves reflected back and forth in the pulse jet interior. Finally, measurements of the velocity of the flambeau A at 5 and 6.5 milliseconds give an idea of the magnitude of these fluctuations. At 5 milliseconds the velocity is 365 feet/second, while that at 6.5 milliseconds is only 40 feet/second. These figures are suggestive, but certainly further and more accurate experimental data must be obtained from a pulse jet known to be resonating freely in a "steady state" before a more detailed and exhaustive analysis can be given, or before the full significance of the present data can be understood.

XII. NOTES ON INSTRUMENTATION

Pressure Pickups. In observations on the transient or periodically varying pressures in jet motors, the pickup device must satisfy certain requirements. It must record oscillating pressure in the range −5 to +45 lbs./sq. in. It must follow complex pressure time variations which recur with a frequency of 50 to 250 cycles/sec. It must be insensitive to gas jet temperatures in the range 20–2500 C. Standard commercial gauges are of little use on jets because of the temperature range and the vibration.

Systems employing deep wells and mechanical linkages to the operating unit are generally unsatisfactory because of resonance and vibration.

We have designed a water-cooled baffle which may be used just in front of the operating diaphragms of magnetostriction, crystal, or condenser type gauges. A magnetostriction gauge has been designed, but construction has been delayed by a scarcity of magnet steel.

An integrating circuit will be used with the magnetostriction gauge, and the output will be applied to an oscilloscope.

The condenser gauge will be used to modulate a FM circuit. To avoid difficulties with the impedance of the cables, a system of preamplifiers at the jet is being considered. A crystal gauge is being tested, and construction of others is being planned.

The oscilloscope screen can best be studied in all cases with the help of the General Radio camera.

For calibration purposes we are considering the construction of an adiabatic pressure chamber with a mechanically oscillated diaphragm.

Temperature Pickups. A photomultiplier pickup with an amplifying system has been constructed (See Section XIII). In observations on the light from burning gasoline vapor this apparatus may be used to measure (1) direct intensities of the sodium D-line, (2) absorption intensities of the sodium D-line, (3) relative intensities of the sodium line and the potassium line, and (4) the intensity of the continuous background.

It is clear that for the first three methods the gasoline must be well "saturated" with sodium. At present the best method of doing this is to spark metallic sodium under gasoline, the operation being done in an oxygen-free nitrogenous atmosphere.

The fourth method listed above also offers considerable possibilities. Preliminary spectroscopic study of the flame in glass model jets shows many bright regions of the continuous background, uncrossed by emission lines. The photomultiplier tube is sensitive enough to allow the use of filters. Consequently, an optical system in conjunction with two photomultiplier tubes has been designed so that intensity pickups from two parts of the spectrum can be applied to the X and Y plates of a cathode-ray tube for simultaneous observation.

Velocity. Direct measurements of flame velocities relative to the flame tube are made with the Eastman III Hi-Speed Camera. This camera has also been used several times for observations on the resonating glass-walled model jet.

The Bureau of Ships, Navy Department, has promised us two parabolic mirrors. With these we plan to study schlieren patterns of the moving eddies in the jets.

It would be desirable to study the motion of luminous small particles in the flame in order to investigate the details of turbulence, but no practical technique has been worked out.

Density. The instantaneous average density may possibly be measured by observing the scattering of light or of particles. The most promising method seems to be to use either alpha particles or neutrons. We are considering the effect of the combustion processes on the average nuclear cross section. This part of the project is still in the discussion stage.

XIII. THE MEASUREMENT OF FLAME TEMPERATURES IN PULSE JETS BY INTENSITY RECORDING OF SODIUM D-LINE RADIATION

Introduction. It is desired to design and to construct an instrument capable of producing an accurate record of the oscillating temperature at a given point in an operating pulse jet motor.

This instrument must be capable of recording temperature oscillations at a fundamental frequency of the order of 200 cycles/sec. or less and must be fully responsive to harmonic frequency components up to a limit of 2,000 cycles/sec. or more. This "recording thermometer," furthermore, must not be subject to unknown radiation or other losses or to destructive action from the hot gases of the jet, nor must the insertion of the instrument (if insertion into the engine is necessary) result in additional perturbation of the flow of gases in the jet.

It appears that none of the conventional temperature pickups, dependent upon the following physical variables, is ideally applicable to the problem under consideration:

a. coefficient of linear or volume expansion,

b. temperature coefficient of electrical resistance,

c. thermal electromotive force.

Resistance thermocouples or expansion elements introduced into the gas might soon be destroyed by the hot gases, or would at least have their calibrations altered so as to make reproducible measurements impossible. There is also the effect of possible catalytic action of the thermometer pickup device due to the chemical reactions occurring in the flame. Furthermore, under non-steady conditions the design of a radiation shield is subject to grave difficulties. Moreover, the introduction of the pickup element into the engine could conceivably disturb the existing mode of flow of the jet gases. In addition, all the above physical elements are subject to lag and hysteresis; it could never be reasonably anticipated that the hot gas in the immediate vicinity of the probe would come to instantaneous thermal equilibrium with the latter.

Due consideration having been given to the above factors, recourse has been made to an optical method in which the output of an electronic photometer, employing a photomultiplier tube as the radiation pickup element, is used to obtain an oscillographic record of the instantaneous temperature of a portion of the flame in a jet tube. This method, its justification, and the details of construction and calibration of the apparatus are given in the following paragraphs.

Description of the Method and Its Justification. It is advisable first to consider what actual meaning is to be attached to the term "flame temperature." Indeed it has been suggested that a flame cannot have a temperature in the strict sense of the word, because it is not a system in strict equilibrium. But a sufficiently "thick" flame may radiate as a black body, at least for certain spectral bands or rather narrow line breadths, and for such we can apply the Planck formula directly to correlate the spectral intensity with an absolute temperature of the radiating flame.

If a flame is colored by the introduction of sodium vapor or a vapor containing some compound of sodium, there is a point beyond which an increase in the thickness of the flame does not increase the intensity of the sodium D-line observed spectrographically. This experimental fact can be checked by passing the light from a second sodium flame through the first and into a spectrograph, and observing that if the first flame is thick enough, no increase in D-line brightness results.

Now suppose that the intensity of the D-lines from a sufficiently thick sodium flame is observed to be the same as the intensity of the neighboring region of the continuous spectrum emitted by a simulated black body, such as a tungsten band lamp. Then measurement of the flame temperature, e.g. with a shielded thermocouple, has been found to give a temperature equal to the effective black body temperature of the lamp. Thus, the thick flame radiates like a black body in the spectral region of the sodium D-line.

This experimental fact is the real basis for the so-called sodium D-line reversal method of measuring flame temperatures (Kurlbaum, *Phys. Z.*, *3*, 187, 1902). In this method the comparison of the sodium D-line intensity with that of the continuous spectrum is made by passing the light from the continuous spectrum through the thick flame, thus blocking out the D-line region of the continuous spectrum and replacing it with the sodium flame emission line. The temperature of the radiating "black body" is then adjusted until the D-lines merge into the continuous background.

The above experimental fact is not ordinarily used in justifying the D-line method. A theoretical argument is given which purports to show that the temperature of flames transparent for the D-line can be measured by this method; but additional experimental investigation by MacDonald showed that if the intensity of the lines be altered in a transparent flame by changing its thickness but without actually changing its temperature, the apparent temperature of the flame, obtained by comparison with a continuous background spectrum, is also altered.

The photometric method of obtaining flame temperature measurements in jets is now as follows: The electronic photometer, described later, is calibrated first by observations of the intensity of D-line radiation emitted through, for example, one square centimeter of a thick sodium flame at a known distance and temperature (measured, e.g. by the sodium line reversal method). Then the photometer is used to pick up D-line radiation emitted through one square centimeter of the flames in transparent walled jets. These flames are colored by the introduction of sodium compounds into the fuel. If the flames are thick enough in relation to the concentration of sodium vapor, the intensity of the radiation is strictly a Planck's function of the flame temperature (according to the above experiment). The calibration permits the photometer response to be interpreted immediately in terms of temperature.

Apparatus. Figure 19 shows the electrical circuit of the multiplier tube and power supply. In the diagram the output from the tube is led off at points A and B to the amplifier and cathode-ray oscilloscope.

Figure 20 is a sketch of the mechanical and optical arrangement. Light from the flame is let into a closed chamber through a main lens at the front. This falls on the photo-sensitive plate of the 1P21

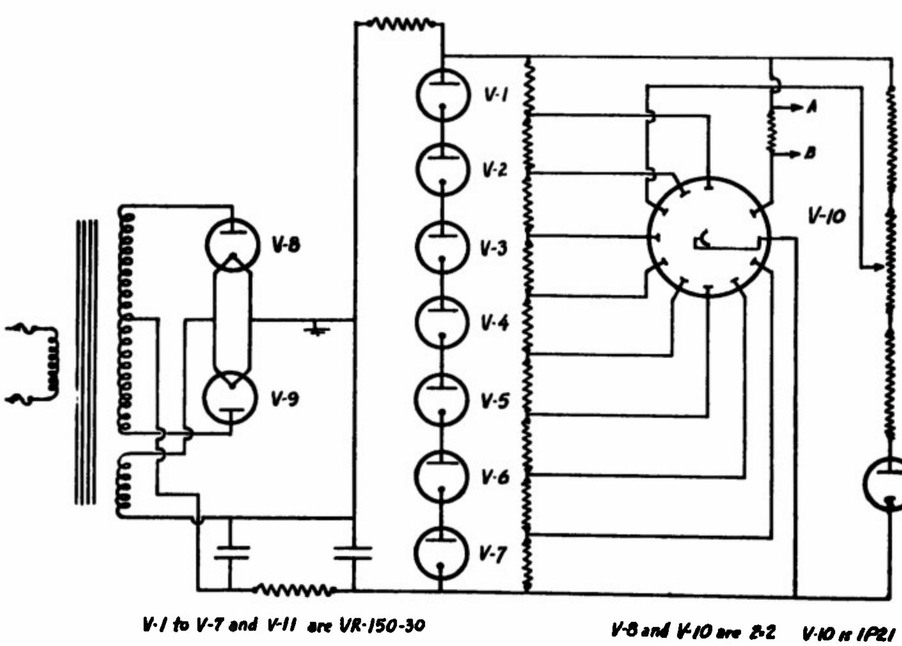

Figure 19. Electrical circuit of electro-optical pyrometer.

multiplier tube which is mounted in the chamber on a screw adjustment so that the focus can be regulated externally.

Results. The pyrometer has not yet been calibrated, but it has been tested for sensitivity in observation of flames. The sensitivity is extremely high, but no detailed data can be supplied at this time.

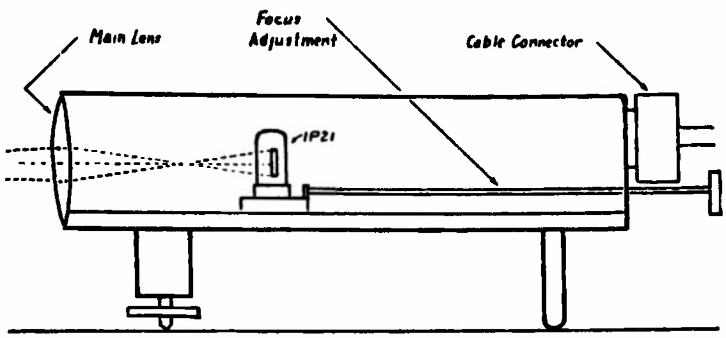

Figure 20. Mechanical arrangement of electro-optical pyrometer.

XIV. DRAG COMPONENTS OF PULSE JET MOTORS

The division of the forces acting on a pulse jet motor into thrust and drag is largely a matter of convention. In practice, this division depends on the conditions of measurement. In some work conducted at Wright Field the total aerodynamic force on a non-firing pulse jet motor mounted on a thrust stand in a wind tunnel was measured with the intake valves in the open and closed positions. The drag was found to be much greater with the valves open. On the other hand, under normal operating conditions the valves open and close periodically, the exhaust modifies the air flow near the tail, and the velocity of the vehicle is somewhat pulsed. All of these factors confuse attempts at correlation with the wind tunnel measurements. If each surface of the motor is classified, according to some common sense convention, as *internal* or *external*, then a natural definition for gross thrust is the vector integral over the elements of the internal surfaces of the components of the aerodynamic forces perpendicular to the elements of the *internal* surfaces. The remaining forces may be defined to constitute the drag and they include skin friction over the internal and external surfaces and also the vector integral over the elements of the external surfaces of the components of the aerodynamic forces perpendicular to the elements of the *external* surfaces. The detailed calculation of the various forces is beyond present knowledge, but some contributions can be estimated on the basis of idealizations such as are indicated below.

Gross Thrust. A mathematical framework for the one-dimensionalized treatment of the thermo- gas dynamical states and pressure waves in pulse jet motors is given in the AMG-NYU Report No. 151 which has been referred to in footnote 1, page 1. When combustion and intake valve parameters have been determined experimentally, they may be used in this framework to estimate the pressure as a function of position and time in a pulse jet. Alternatively, when suitably checked instrumentation has been developed, the pressure function can be determined experimentally. When the pressure function is known, the gross thrust as defined in the preceding paragraph can be calculated as a function of time.

Skin Drag. The skin drag on bodies of revolution in a steady flow has been treated quite exhaustively (see, e.g., Goldstein, *Modern Developments in Fluid Dynamics*, Vol. 1, Oxford, 1943). It is of some interest in connection with pulse jet motors to investigate theoretically the effect on skin drag when small oscillations are superimposed on a steady flow. (It is of course quite certain that the drag due to flow around the sharp edges of the air intake valves is much greater than the skin drag on the smooth external surface of the jet tube. The former is unfortunately most intractable theoretically, but it is to be investigated experimentally at N.Y.U. using the valve grid from a JB-2 motor supplied by the A.A.F.)

In order to make theoretical estimates of skin drag on the external surfaces of pulse jets, the following idealized model is considered. A long torpedo shaped solid of revolution is placed in a slightly pulsed subsonic air stream directed parallel to the axis. Outside a thin boundary layer around the solid, the pressure P and tangential velocity U of the air are regarded as determined by nonviscous flow theory (in particular by incompressible potential flow if the speed is sufficiently subsonic). In the boundary layer the gas dynamical equations are as given in Section 51 of Goldstein's book (referred to above), and are

$$(1) \qquad \begin{cases} u_t + u\,u_x + v\,u_y = -\,(P_x/\rho) + \nu\,u_{yy} \\ (r\,u)_x + (r\,v)_y = 0 \end{cases}$$

Here x and y are distances measured respectively tangentially and normally to the surface of the solid (of local radius r), u and v are corresponding components of velocity of flow relative to the solid, t is the time, P is the pressure already defined above, ρ the air density, ν the kinematical viscosity (assumed constant), and the subscripts refer to derivatives (e.g. $u_t = \frac{\partial u}{\partial t}$). If u, v, and P are each regarded as the sum of two parts, one steady in time and the other oscillating with a relatively small amplitude and with the pulse period T, then by integration of (1) over a period we find that

$$(2) \qquad \begin{cases} \bar{u}\,\bar{u}_x + \bar{v}\,\bar{u}_y = -\,\overline{(P_x/\rho)} + \nu\,\overline{u_{yy}} \\ (r\,\bar{u})_x + (r\,\bar{v})_y = 0 \end{cases}$$

if products of the small oscillating terms are ignored, and if bars represent time averages of the quantities concerned. Equations (2) have the same form as those for steady flow and can be treated in an analogous way in order to find the shearing stress, $\rho\nu u_y$, at the surface of the solid. Therefore, for the case of small oscillations superimposed on a steady flow, the usual steady flow formulas for skin drag (on surfaces ahead of lines of separation of flow) can be employed if time average values of the pressures and velocities are employed. The contribution to velocity oscillations from the oscillating thrust of a pulse jet is small under practical conditions. Thus if the mass of the flying pulse jet vehicle is M pounds, the cycle frequency $\omega/2\pi$, and the net instantaneous thrust under "steady flight" conditions is $T = T_o \cos \omega t$ poundals, it then follows that the velocity V of the vehicle satisfies the following equation of motion:

$$M\,V_t = T_o \cos \omega t$$

Integration and use of $\overline{V}$ for the average velocity yields

$$V = \overline{V} + \frac{T_o}{M\omega} \sin \omega t$$

In a practical case $\overline{V}$ is a few hundred feet per second while the amplitude of the second term is considerably less than a foot per second. On the other hand the contributions to the air flow oscillations over the surface of the jet tube, due to aspirator and other effects produced by the pulsating intake and exhaust, are conceivably not so small. Experimental investigation of the magnitudes of these last contributions is planned. If these magnitudes are not small as compared with the average velocities, then equations (1) will require a more elaborate treatment than that indicated above. If the experimental investigations do not suggest a simpler attack, it may be necessary to use the methods of difference equations to solve the boundary layer equations (1) subject to the relevant boundary conditions.

Since the usual pulse jet motors run with their jet tubes very hot even on the outside, it is likely that heat transfer between the tubes and the boundary layer may affect the skin drag to a marked extent. A start in the theoretical study of such effects has been made, but the final methods of calculation will depend on magnitudes of temperature and velocity oscillation. These will be determined experimentally when a large test stand becomes available.

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ABSTRACT:

Various phases of research were conducted on liquid fuel rockets and pulse jet engines. Theoretical and experimental investigations were performed on flame motions, thermal conductivity, drag characteristics, and recording instruments. Studies were made on re-ignition and on various steel alloys for construction of pulse jets. Tests were run on small jets for verification of theories and to facilitate designing of larger pulse jet engines.

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AIR TECH INDEX